RECENT INVESTIGATIONS

CONCERNING

THE CONSTITUTION OF MATTER

BEING

A COURSE OF SIX LECTURES

DELIVERED AT PATNA UNIVERSITY

IN

MARCH 1922

BY

E. P. HARRISON, PH.D., F.R.S.E., F.INST.P.

[illegible]

Fellow of Calcutta University

[illegible] College, Calcutta

CALCUTTA

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INTRODUCTION

The University of Patna did me the honour in 1920 to appoint me Reader in Physics and I was asked to deliver a course of lecture during the winter of 1921–22 The lectures under the conditions of the appointment were to be published It is clear that in India at least one part of the University Reader's duty is to codify existing branches of a subject rather than to impart new knowledge the junior staff and senior students are thereby given an opportunity for a general survey of a wide field With this object I have aimed at giving a connected sketch of what I judge to be the principal lines of research which are in progress at the present time From what has been touched on much important work has obviously been omitted many valuable researches have necessarily not even been touched on

In cases where two lines of investigation were regarded as of almost equal significance yet for want of time one had to be omitted I have endeavoured to choose what I believe to be the less accessible An alternative of this kind is presented in the Researches of Bragg on Crystal Structure and of Aston on Atomic weights I chose the latter

In preparing these lectures for the Press I have to some extent rearranged their order for instance—Lecture 4 was actually delivered before Lecture 3 I have also made a few additions notably on the important recent work of Whittaker on Quantum Mechanism and of Ewing on Ferromagnetic Models

E P H

CALCUTTA

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LECTURE I

The directed efforts of physicists during the past decade have taken the form of a peculiarly intensive attack on the intimate constitution of matter. It is true that for hundreds of years the solution of this atom problem has been the final goal of the natural philosopher, but it seems as though recent research has been rewarded by discovery almost more abundantly than in the golden days of Newton. In the race for knowledge something of the nature of a spurt has been made; the last corner seemed actually to have been rounded, but the view, instead of providing the hoped-for glimpses of phenomena comprehensible, revealed a goal more remote than before, lying dimly on the horizon of new and unexplored country.

In fact, discarding the language of metaphor, the solution of the mystery of matter and energy, as the philosopher would always have told us, was perceived to be thrown back on other mysteries perhaps more transcendental than anything previously in man's purview. It is my task in this course of lectures to try to set before you what I conceive to be the more important methods of attack on the constitution of matter which have been developed since the bright and hopeful years which immediately preceded the great war of 1914. It is not of course necessary to remind a University audience that the foundation—the first beginnings—of the new advances to which I have alluded lies in the discovery of the negative electron as a common constituent of all matter. The negative electron is now to us a real entity. There is no room for doubt that down this tube, in which the air pressure is reduced to of a mm of Hg, there passes from the cathode a stream of these negatively charged entities moving freely (on account of the removal of the air molecules) with velocity th or so of that of light, whose mass, unlike any masses known 20 years ago, increases as a definite function of their velocity, and whose electrical charge e has been measured by experiment and found to be always the same from whatever form of matter the electron may have proceeded, and to be moreover the *smallest* charge which has ever been observed and probably one of the *natural constants*. The innumerable instances in modern physics in which the charge on the negative electron is involved make it of the greatest importance to obtain a standard determination of its value.

This has been done by Millikan, and as the method employed seems to open up several avenues for new research and has already yielded results of great interest in connection with the mechanism of ionisation, I shall begin by describing Millikan's experiments

It will be remembered that the manner in which Thomson originally found the value of e is briefly as follows

Positive and negative ions are produced by X rays in a wet gas and the total negative charge F per c c is measured

After a sudden expansion of the gas a cloud is formed the ions acting as condensation nuclei and the weight M of the cloud is obtained by calculation from the density of the saturated vapour The average radius a of the drops is found by observing the rate of fall of the top of the cloud and employing Stokes law Hence $M = \frac{4}{3}\pi a^3 \rho n$ where n the only unknown is the number of drops in the cloud and ρ is the density of water Determining n from this equation we calculate $\frac{F}{n} = e$ the electron charge required

This method assumes that—

(i) There is one and only one ion in each drop

(ii) Stokes law is true for the fall of such drops through a gas

(iii) There is no evaporation during the measurements of the velocity of fall of the cloud

None of these assumptions are strictly true

Millikan s method in its final form depends on the production of a spray of very fine drops of oil which usually have a frictional charge to start with and which can be introduced into the region between the parallel plates of an air condenser (Fig 1) [the plates were optically worked and were parallel to within a few wave lengths of sodium light] If the oil drops are illuminated and an individual drop of diameter perhaps 0003 cm is observed by means of a microscope it will of course slowly fall down on to the lower plate under gravity

If however an electrostatic field is put on the field according to its sign either pulls the drop upwards against gravity or aids gravity in pushing it down Clearly the field can be adjusted to balance the effect of gravity so that the drop either remains stationary or is endowed with any desired velocity of descent Now it was found that if X rays were allowed to ionise the gas between the condenser plates during the observation of the speed of fall of an oil drop an air ion often attached itself to the charged drop consequently the speed of the drop in the field of the condenser changed

From observation of the initial speed of a charged drop and of the change of speed on picking up an ion the following quantities were measured —

(i) Ratio of the frictional charge to the ionic charge and hence the number of electrons actually carried by

the oil drop in virtue of its frictional charge. This number varied on different drops from 0 up to 200 beyond which the accuracy of the velocity measurements were not valid.

(ii) The mass of an oil drop can be determined to $\frac{1}{10\,000} \times \frac{1}{10^6}$ milligram by balancing the field against the gravity effect on a drop with known charge—a remarkable achievement.

(iii) The absolute value of e.

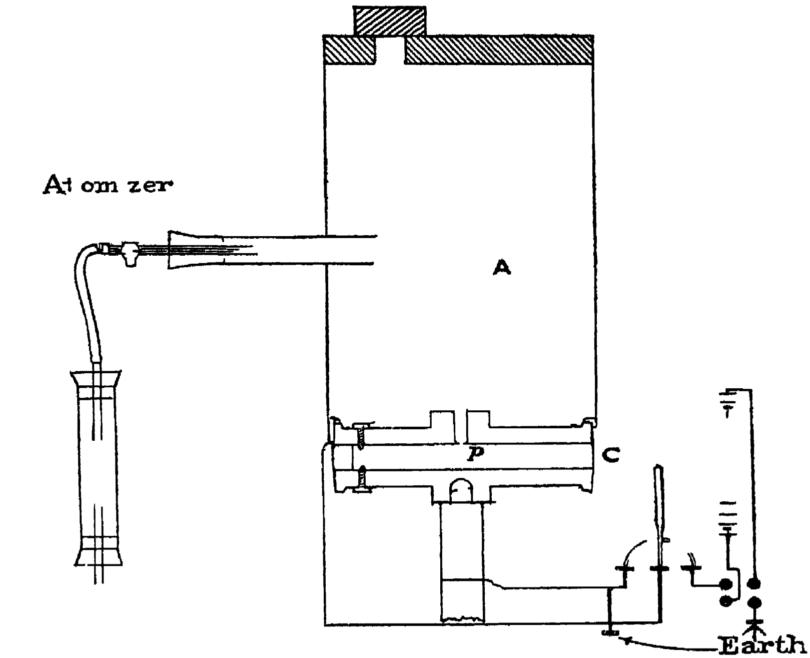


FIG. 1

The accurate measurement of this last quantity which was the primary object of the research involves a knowledge of the conditions under which Stokes' law fails. It is fairly clear that this will begin to set in when the radius a of the drop becomes comparable with the mean free path λ of the molecules of the gas. Indeed the formula is based on the assumption that a is large compared with λ.

Thus a correcting factor of the form $f\left(\frac{\lambda}{a}\right)$ will have to be applied.

Expanding in undetermined multipliers this can be expressed

$$A\left(\frac{\lambda}{a}\right) + B\left(\frac{\lambda}{a}\right) + C\left(\frac{\lambda}{a}\right)$$

whence neglecting squares of $\frac{\lambda}{a}$ we may write the corrected Stokes law $\left(\text{since } \lambda \propto {}^{1}/p\right)$

$$v = \frac{2}{9}\,\frac{ga}{\eta}\left(\sigma - \rho\right)\left(1 + A\,\frac{1}{pa}\right)$$

where v is the velocity of fall of the drop under gravity and ρ are densities of drop and medium respectively a is the radius of the drop η is the viscosity of the gas medium and p is the pressure of the gas

The actual way in which Millikan determined the charge was as follows —

Let e be the required absolute value

e_1 be the apparent value obtained by assuming the uncorrected Stokes law at various pressures

Then by comparing velocities and employing the corrected Stokes law it can be shown that

$$e = e_1\left(1 + A\,\frac{\lambda}{a}\right)^{-3/2}$$

or

$$e_1^{2/3} = Ae^{2/3}\left(\frac{\lambda}{a}\right) + e^{2/3} \qquad (1$$

which if $e^{2/3}$ is a constant and the modified Stokes law is true is linear in $\frac{\lambda}{a}$. On ploting $e_1^{2/3}$ against $\frac{\lambda}{a}\left(= {}^{1}/pa\right)$ a straight line is actually obtained (Fig 2). The value of e is then chosen by extrapolation from this line which corresponds to $\frac{1}{pa} = 0 = \frac{\lambda}{a}$. Hence for this value of e_1 the free path term does not come in and $e_1^{2/3} = e^{2/3}$ from (1)

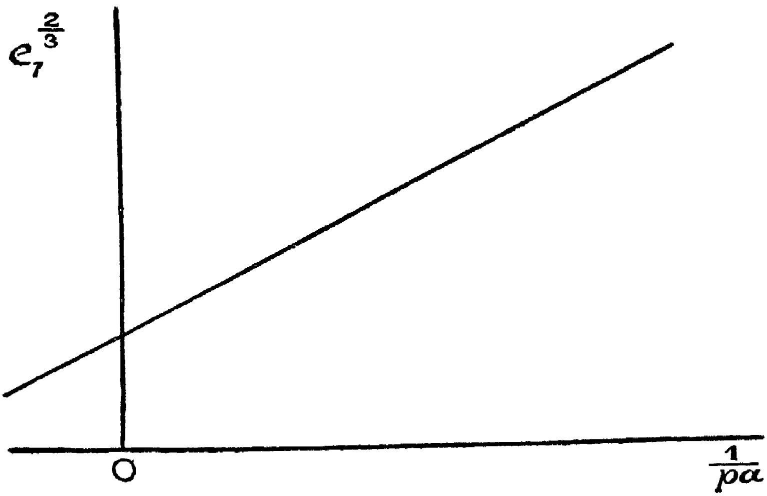
The final value of e the result of these measurements now generally accepted as a standard gives

$$e = 4\ 774 \times 10^{-10} \pm\ 005 \times 10^{-10} \quad \text{electrostatic units}$$

The importance of a standard determination of this charge e is obvious when it is realised how many physical quantities depend on it. For instance it enables the mass of the negative electron (9×10^{-24} grams) to be found from the measured values of $\frac{e}{m}$ the

radius of the electron ($1\cdot 9 \times 10^{-13}$ cms.) is then calculable from theoretical formulæ, while a knowledge of e is also needed in finding the absolute mass of any atom, and in questions concerning X-ray wave lengths and Planck's radiation constant.

Millikan in more recent work has employed the method of balanced drops to investigate the number of electrons lost by a gas molecule when ionised. It is found that when the ionising agent is X rays or β or γ rays from radium, in *every* case only one electron is detached from the molecule, leaving a singly charged ion. When X rays are used, in 99 cases out of 100 a single electron



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is detached. The remaining 1 per cent of cases apparently give a doubly charged ion.

The method seems to have yielded already a great deal of information on the mechanism of ionisation which bears directly on the constitution of the gaseous ion.

Let us turn now to the much more subtle problem of the constitution of the negative electron.

Side by side with the mass of direct experimental evidence for the existence and principal properties of minute charges in

The indefiniteness of the expression "radius of the electron" is recognised, and one meaning at least is avoided too below. It must not be assumed that the electron is conceived of as a discrete particle with a sharp boundary; nevertheless, if only for brevity, it is hardly possible to avoid attributing a definite radius to the region occupied by the negative charge, even though all such instances must be interpreted in the sense indicated by electromagnetic theory.

motion there has grown up in the writings of Kelvin Lorentz J J Thomson Abraham and Larmor a purely theoretical electron which has been developed largely with the object of accounting for the known phenomena but which in some directions has anticipated discovery

The basis of all theories of the electron and of its behaviour when in motion lies in the arbitrary assumption of a local modification in space to which the ordinary electro magnetic equations or equations derived from the Maxwell system but modified according to the theory of Relativity can be applied Of the nature of these local modifications or regions of definite volume density we have no physical conception We merely assume that the localised electric *charge* whatever that may mean is subject to the action of force—which is the electric force Moreover the charge may have any distribution It is evident however from the essentials of the theory that the total volume over which individual charges are distributed must be exceedingly small in comparison with the total volume of any portion of matter which can be directly observed In calculating the work done in giving a velocity v to a charge (thus obtaining an expression of the form $\frac{1}{2}Mv$ (where M is analogous to a mass) various assumptions have been made as to the distribution of the charge For instance J J Thomson assumed a point charge at the centre of a small sphere of radius r and found this radius on the assumption that the ratio of the electrical energy outside the region to that inside is negligibly small (See foot note page 7)

Abraham on the other hand assumed the charge to be distributed on the surface of a conducting sphere The result in both cases (when the velocity is not more than one tenth that of light) indicates that the moving charge behaves as though its original mass (if any) were increased by a purely electrical mass [illegible]

where A is a numerical factor slightly different on the two hypotheses

As the speed of the electron approaches that of light this electromagnetic mass increases rapidly In order to calculate the relation between velocity and mass various conceptions have been adopted as to how the dimensions of the electron are affected by its velocity For instance Abraham assumed constant dimensions at all speeds which gives a rigid electron whereas Lorentz regarded the electron as contracting in the direction of motion The two methods give a different relationship between v and the mass but whichever hypothesis is adopted the general conclusions are the same —

(1) when the centroid is accelerated the electron radiates energy

(ii) the apparent mass is proportional to the speed and the mass for transverse accelerations (at right angles to the direction of motion) differs from that for longitudinal accelerations when the velocity is high

Now the measurements of Bucherer on the variation of mass with velocity of particles from Radium fluoride are in agreement to 1% with the theoretical relation given by Lorentz thus confirming the contractile theory of the electron and incidently supporting the Relativity theory In addition this confirmation of the theoretical formula shows that electronic mass is wholly electromagnetic for if any part of it were ordinary material mass the observed variation with speed would be less than that given by either of the theoretical formulæ both of which are based on a purely electromagnetic hypothesis

Although the usual form with which the electron has been endowed is that of a sphere [in the Lorentz type changing to an oblate spheroid when in motion] the investigation of other forms has perhaps been governed more by the limitations of mathematical analysis than for any definite physical reason

Of recent years however several experimental results have been obtained which indicate that it will be necessary to pay more attention to the structure of the negative electron itself if we are to succeed in explaining those results on the basis of an electron theory at all The experiments I refer to are four in number

I When X rays fall on a plate say of aluminium the rays are scattered forwards backwards and sideways The distribution is however asymmetric the forward intensity exceeds the backward intensity and is not altogether in conformity with the ordinary theory of the interaction of X rays with the electrons in the scattering plate

II Forman has observed that iron has a greater absorption coefficient for X rays when magnetised parallel to the X ray beam than it has when unmagnetised In other words the energy scattered would appear to be a maximum when the iron is magnetised along a definite axis

III The ionisation produced by X rays is exceedingly small in a gas at the most it only results in the production of one ion for every 10^{1} gas molecules Why should this be? It looks as though there may be only one plane in which the electron can absorb enough energy from the pulse to effect ionisation

IV It has been observed by C T R Wilson that the paths of β and secondary cathode rays excited by X rays in air and examined by stereophotographs usually terminate in converging helices The helices may be right or left handed and the axes are apparently orientated at random

It does not seem easy to account for any of these observations on the ordinary unstructural electron theory.

The most promising type of electron structure which has been hitherto propounded is probably the ring electron suggested by McLaren in 1913 and by Parson in 191[illegible], and used by the latter in building up a new atomic theory. Of this theory I shall have occasion to speak later, but it would not be appropriate to conclude this lecture without some description of the ring electron itself. It is regarded as the limiting surface of the aether, shaped like

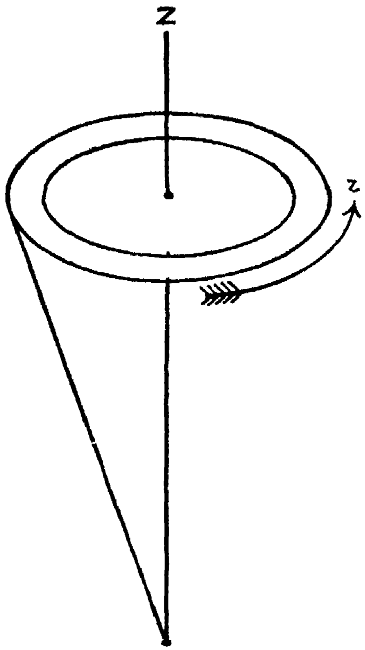

FIG. 3

an anchor ring. Tubes of electric induction end on the surface and give it a charge. The charge is rotating round the ring with the velocity of light.

Magnetic tubes will of course be linked through the ring, making it into a minute permanent magnet. Its size is estimated by Parson to be of the order of 10^{-9} cm. Thus the ring is conceived by him to be somewhat smaller than the ordinarily accepted diameter of the *atom*, which is 10^{-8} cm.

The ring electron has been described by Larmor as an Amperian molecular permanent current, and he points out that the

thing is not really a physical unit—for instance a series of elec trons constrained to revolve round a channel would behave in the same way Thus the new conception so it appears to me really lies in assuming that such channels have an independent existence

The total angular momentum of a ring electron is a quantity which has a bearing on the structure of the ferro magnetic atom and which will be referred to in a subsequent lecture

It can be calculated quite easily as has been shown by Allen

Each Faraday tube is rotating round the Z axis with angular velo ω (fig 3)

The equivalent mass of a tube per unit volume $=4\pi$ N where N is the electric polarisation

If $\delta\Omega$ is the angular momentum per unit volume

$$\delta\Omega = 4\pi\rho N \ (r \quad)$$

but the magnetic field is $= H = 4\pi N r$

Hence

$$\delta\Omega = \frac{\mu H}{4 \ \omega} = \frac{-}{} \left(\frac{\mu H^2}{8\pi}\right)$$

and the total momentum is $= \frac{-}{\omega} \times$ the energy of the magnetic field

$$= \frac{-}{\omega} \times \tfrac{1}{2} L i^2 = \frac{L}{\omega}$$

where L is the coefficient of self induction and i is the current

Now $I = N$ = the number of magnetic tubes linked through the electron

and $\omega = \frac{e}{2\pi} = \frac{Ne}{2\pi}$ where N is the number of electrostatic tubes

therefore $= \frac{1}{2\pi}$ V V

This is *independent of the* ... *of the* ...

On the assumption that electrons of this kind go to build up the structure of the atom a qualitative explanation is afforded of the asymmetric scattering experiments the X ray absorption in magnetised iron and the small amount of ionisation in gases

In each of these cases the effect observed would be due to an asymmetry in the electron itself and not to the atom as a whole for Bragg's experiments have shown that in X ray diffraction and absorption the electron is the entity involved In the case of the Wilson helices it is suggested by Shimizu that the electron has a definite magnetic polarity which on account of gyrostatic action does not change rapidly in direction The introduction of the

ring electron would be expected to induce magnetisation in the surrounding air molecules and this would have the same effect on the electron as an external field of the same intensity In these circumstances the path would be a helix converging as the velocity of the electron decreased

When we attempt to build up a theoretical atom on the basis of the negative electron as it is known various considerations arise involving us in entirely new hypotheses Whatever may be the detailed structure of the negative electrons it is evident that since they form an important part of all atoms they must be associated in any particular atom so as to produce a complex which is not only stable but electrically neutral Neutrality is supposed to be attained by giving the atom in addition to its negative electrons a distribution of so called positive electricity Such an assumption is of course arbitrary but certainly positive charges are observed in association with matter In any case no one has suggested an alternative controversy has merely centred round the form of the positive distribution The only difference so far as calculation is concerned between an element of positive charge and one of negative is the difference which forms the basis of the well known definitions of electrostatics no physical conception of the expression charge either positive or negative has ever been proposed it remains one of the fundamental mysteries and the question of its two fold nature is unanswered and almost unasked

It is remarkable that considerations of the Relativity of Space and Time lead to the conception that it is electric charge rather than mass which is conserved in the universe

How the other quality of the atom stability is supposed to be attained I reserve for a subsequent lecture

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LECTURE II

The attempt to discover the mechanism of the atom has developed during the past few years along two main lines

The first may be likened to the methods of an Intelligence Department in the Army The second to those of an Adjutant General s or Fighting Branch the section of direct frontal attack The Intelligence Department occupies itself in observing and classifying the automatic records produced by the atom and exhibited in such phenomena as spectra spectral series thermal radiation X ray emission Radioactivity Having collected a large number of facts under these heads the attempt is made to invent an atom which by its behaviour under various conditions would be expected to reproduce the observed phenomena

In this attempt all the resources of man s knowledge ingenuity and mathematical skill are available but naturally it is impossible to work backwards and to infer from the spectra or other phenomena what kind of atom to start with The atom must be invented *de novo* its behaviour deduced and the result compared with the facts Acting alone this process would give a tremendously wide latitude for hypotheses of atom structure

By good fortune however the other Department of research to which I have alluded and which has quite recently been developed provides us with certain limiting conditions to which all atoms must initially conform These conditions are the result of direct experiment on the atom itself hence it is impossible to ignore them when designing the architecture of a model Indeed if the experiments are sound any discussion of atom mechanisms which do not conform would probably be waste of time

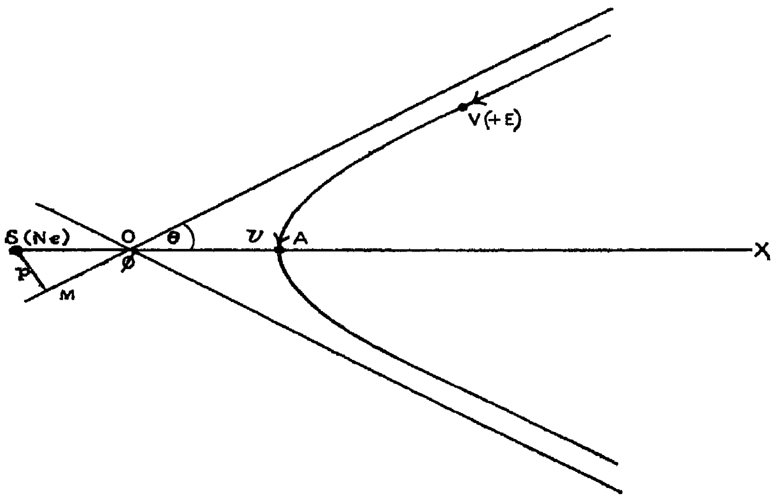
In the present lecture I shall review some recent work in which a direct frontal attack of this nature on the atom has been carried out by bombarding matter with high velocity projectiles in the form of particles from radium C and shall consider the limiting conditions which have been determined

The first experiments of the kind were performed by Geiger and Marsden in 1909 and are still proceeding under the auspices of Sir Ernest Rutherford and his students

As you are doubtless aware an particle is a helium atom which has lost two negative electrons and possesses therefore a charge of $+2e$ It possesses practically all the mass of the atom (which is $6\ 5\times10^{-24}$ gram) and its speed in air at N T P is known to be of the order of 10^9 cm/sec (=12000 miles a second) before it reaches the end of its range When a single particle strikes a screen made of fine hexagonal zinc sulphide crystals it causes a scintilla

tion and thus advertises its presence The number of scintillations caused by a beam is thus the actual number of particles striking the screen If a stream of these high velocity massive particles is fired at a thin plate of matter such as a film of gold they pass right through it and their behaviour on emerging from the film can be examined by a zinc sulphide screen held at a suitable distance

It might have been expected that the particles would be enormously scattered by impact with the gold atoms It was found however that only very occasionally was a particle seriously deflected the large majority suffered practically no deflection In fact the gold was very highly porous to particles It is on



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these occasional large angle deflections that I would ask you to fix your attention

Let us consider the conditions which might hold during collision between an α particle and a gold atom The gold atoms are doubtless built up of some distribution of negative electrons arranged in the outer portion of the atom They are presumably held in equilibrium by the positively charged portion of the atom which possesses most of the atomic mass As to the distribution of that positive charge there were various opinions at the time these experiments were made The Kelvin Thomson theory so well known to you all supposes a positively charged sphere of atomic dimensions in which the electrons are in orbital motion Other suggestions included the idea that the positive electricity was concentrated in a very minute region near the centre of the atom

The deflection results just described appear to decide quite definitely between these two views For the deflecting effect of the negative electrons can easily be shown to be negligible if the α particle really penetrates deeply into the atom So also would be the effect of a distribution of + electricity over a sphere of atomic dimensions regarding the sphere as possessing only electromagnetic mass Consequently it must be inferred that the massive part of the atom associated with the + electricity is exceedingly concentrated for if not the large angle deflections of the particles would have been far more numerous

The gold atom in fact is a very open system through which the particle can in general penetrate almost unchecked If however an particle by chance impinges directly on to the charged nucleus a large angle deflection is precisely what we should expect Such in general terms is the argument for a small nucleus derived from the earlier experiments of Rutherford Geiger and Marsden I will now consider in some detail a few of the simpler calculations on which these deductions are founded

Consider a collision between an particle and a positively charged nucleus at S (fig 4) It is assumed in the first place that the inverse square law of force holds between the nucleus and the α particle and that both are to be treated as point charges Call the nuclear charge Ne where N is an integer

Let the particle be projected along XS with velocity V directly towards the centre of the atom The potential at a distance b from the centre of the atom (where b is very small compared to the radius of the atom) is

$$Ne\left(\frac{1}{b}\right)$$

Hence the α particle will be brought to rest at a distance b from the centre given by

$$\frac{1}{2}mV^2 = NeE\,\frac{1}{b}$$

whence
$$b=\frac{2NeE}{mV^2}$$

Now let the particle be projected as in the diagram non centrally Considering the angular momentum we have

$$\frac{V}{v}=\frac{SA}{p}$$

where p is the perpendicular from S on to the asymptote and v is the velocity of the particle at its point of closest approach to S

From the conservation of energy

$$\frac{1}{2}mV^2=\frac{1}{2}mv^2-\frac{NeE}{SA}$$

therefore $$\frac{v^2}{V^2} = 1 + \frac{b}{SA}$$

But the eccentricity of the hyperbola is

$$e = \sec\theta = \frac{SO}{OA}$$

and by geometry

$$SA = SO + OA = p\cot\frac{\theta}{2}$$

also $$b = 2p\cot\theta$$

thus the angle of deviation $= \phi = \pi - 2\theta$ is given by

$$\cot\frac{\phi}{2} = \frac{2p}{b} \tag{1}$$

Now suppose the α particles fall normally on a plate of matter of thickness t

Let n be the number of atoms per unit volume

R the radius of an atom

Then the number of collisions of an α particle with the atoms is $\pi R^2 nt$. The probability m of an α particle entering an atom within a distance p of its centre is given by

$$m = \pi p^2 nt$$

The fraction of the total number of particles deviated between ϕ and $\phi + d\phi$ = the probability dm of their striking within radius p and $p + dp$

From equation (1) this is given by

$$dm = 2\pi p\,nt\,dp = \frac{\pi}{4} nt b^2 \cot\frac{\phi}{2}\operatorname{cosec}^2\frac{\phi}{2}\,d\phi$$

Let Q be the total number of α particles falling on the plate of foil (fig 5)

The total number deviated between ϕ and $\phi + d\phi = Q\,dm$ where dm is the fraction of the whole number deviated therefore the total number y deviated per unit area of the screen at distance r from the plate is given by

$$y = \frac{Q\,dm}{2\pi r^2 \sin\phi\,d\phi} = \frac{ntb^2 Q \operatorname{cosec}^4 \phi/2}{16r^2}$$

$$= \frac{nt}{16r^2}\left(\frac{2NeE}{mV^2}\right)^2 \frac{1}{\phi^4} \quad \text{for small values of } \theta$$

Thus the number of scintillations per unit area at a distance r from the plate is proportional to $1/\phi^4$ for small angles for a given plate and constant velocity of α rays

The experiments of Geiger and others agree well with this deduction from the theory and the value of b (distance of closest approach during the largest deflection) is found to be 10 cms

Recalling the hypotheses on which this theory is based such good agreement with experiment affords strong evidence that down to distances of 10 cms from the nucleus the inverse square law is true and that the charge occupies such an exceedingly minute region of space that it can be treated as a point charge

In later experiments Rutherford replaced the metal foil by

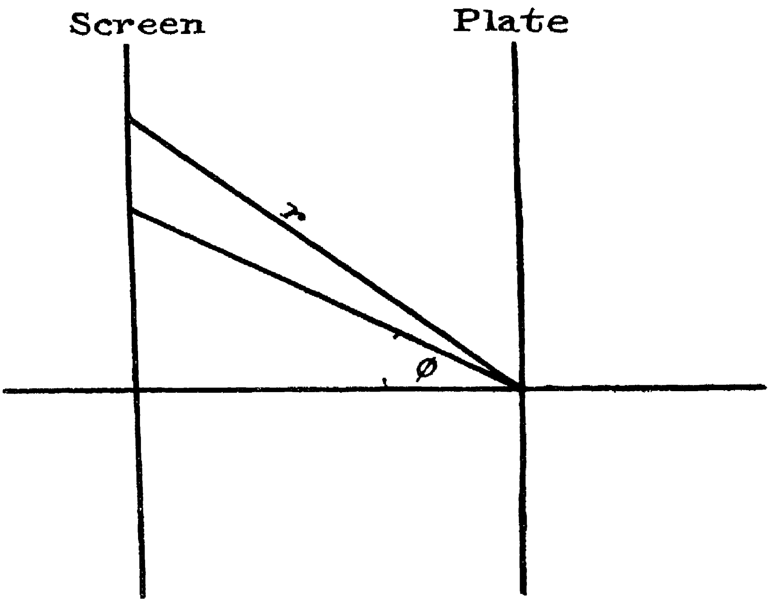

Fig 5

hydrogen gas Now the range of particles from radium C in hydrogen was quite definite being about 7 cms

On bombarding the hydrogen it was found that the passage of the particles gave rise to scintillations on a screen placed far beyond the range of the particle itself four times as far in fact The natural explanation appears to be that the hydrogen atom or part of it was shot forward by the collision and itself produced a scintillation on the screen It was found as the result of experiment

1 That the atoms whatever they might consist of were propelled in the direction in which the particle was moving

2 That the velocities were distributed over a small range that is they all had nearly the same velocity

3 That the particle and the nucleus of the hydrogen atom approached within a distance of 3×10^{-3} cms during a collision

Now Darwin has obtained an expression for the number of long range atoms of charge $+e$ to be expected as a result of collisions with bombarding particles of charge $+2e$ *assuming the nuclei act as point charges under the inverse square law*

The number observed experimentally does not agree with Darwin's calculations It is much greater than theory indicates There are three possible explanations

Either (i) the assumed charges $+e$ and $+2e$ are wrong

or (ii) the nuclei do not act as point charges but as structures of finite size

(iii) the law force is wrong at these small distances

If particles of smaller range (4 cms) and smaller velocity are used the Darwin law is much more nearly obeyed Thus in these cases Darwin's assumption both as to the charges and the force law must be correct or very nearly so It appears then that when the approach of the nuclei is not so close the charges and law of force are correct and the nuclei act as points Hence it is concluded that for the closer approach of the swifter particles (range 7) the most likely solution is not that the law of force itself suddenly alters but that the nuclei no longer act as point charges at distance of 10 cms

It is interesting to realise how very few particles come into collision with H atoms only one in 100 000 of particles in one cm of hydrogen gas at N T P gives a swift H atom Each particle passes through the sphere of action of 10 000 H molecules in its flight through 1 cm of the gas

It has also been shown by Rutherford that the H nucleus behaves as an independent unit and swift H particles are produced equally well from combined hydrogen

Additional confirmation that these swift atoms are really hydrogen with a + charge has been obtained by the measurement of their mass and velocity by the deflection method

They are found to be atoms of charge +1 and mass 1 relative to oxygen = 16 and the value for $\frac{\text{charge}}{\text{mass}}$ is 10 e m u Now the electrolytic value of $\frac{\text{charge}}{\text{mass}}$ for hydrogen is 9570 e m u hence the atoms are undoubtedly hydrogen of charge +1 which means that they are probably hydrogen nuclei

It may be that the positive nucleus of hydrogen is in reality the positive electron or proton having purely electromagnetic mass If this is true it is easy to calculate its diameter since its mass and charge are known

Thus if M and m are the masses of nucleus and negative electron respectively both being purely electromagnetic R and r their respective radii

Then since they have the same charge e (by hypothesis)

$$R = 4 \frac{e^2}{M}$$

$$r = 4 \frac{e^2}{m}$$

$$R = \frac{m}{M} = \frac{1}{1830} \times 1.5 \times 10^{-13} = 10^{-16} \ cm$$

Thus on this hypothesis the radius of the atom nucleus is [illegible] the radius of the negative electron

Its extreme minuteness is borne out as we have seen by all the deflection experiments

Since the helium nucleus (α particle) has nearly four times the mass of the H nucleus it is inferred that the former contains four positive electrons (H nuclei) and two negative electrons associated very closely Thus its net charge is $+2e$ Since in radioactive transformations particles are produced but never H atoms it is further inferred that the combination of H nuclei with negative electrons to make an particle is extremely stable

We may sum up the results as follows Experiments on scattering for heavy atoms like gold show that the nuclei behave as points down to distances of 10 cms whereas the hydrogen experiments indicate that the law fails to hold for closer approach than 3×10^{-13} cms It would appear then either that we must get some distortion of the H nucleus and the particle produced by the intense forces when they approach to within this distance of each other or that one or other of them behaves asymmetrically during a collision The calculated value of the repulsive force between two nuclei on a close approach reaches the enormous value of 5 kilograms weight !

Still more recent discoveries resulted from some experiments on the absorption of the propelled atoms by gases

When columns of oxygen or CO were used the absorption followed the usual law When however dried air was used the number of scintillations increased instead of diminishing

Now particles in oxygen and nitrogen give rise to atoms of range 9 cms in air and are probably swift oxygen or nitrogen atoms carrying unit charge and produced by collisions

Therefore in the experiments now being described those atoms were dealt with which were propelled with ranges *greater* than 9 cms.

These long range atoms from air were proved not to be due to hydrogen from water vapour nor were they due to hydrogen impurities nor to H atoms from dust nuclei in the air; neither was there any change in the phenomenon when chemically prepared nitrogen was substituted for air. As they were not produced in oxygen it was necessary to attribute them to nitrogen. But nitrogen atoms have only a range of 9 cms. so the new particles cannot be nitrogen itself.

The value of their mass and velocity was determined by the deflection method and yielded strong evidence that the atoms in question were hydrogen. Further comparison of the deflection of atoms known to be hydrogen with the new atoms amply confirmed this. The only conclusion remaining is that the nitrogen nucleus itself is disrupted by the collision and charged hydrogen nuclei are knocked out. It is calculated that only one α particle in 300 000 approaches the nitrogen nucleus near enough to liberate hydrogen atoms with enough energy to be detected. Many may however be liberated with smaller velocities and absorbed before reaching the screen.

In addition to the long range atoms from nitrogen with which I have just dealt there are produced atoms of shorter range but still greater than that of the α particle which produce them.

There is strong experimental evidence for believing these short range atoms from nitrogen and also from oxygen to be atoms of mass 3. They are produced in greater number than the H atom. It is therefore suggested that a group of mass 3 is a regular constituent of the nuclei of both nitrogen and oxygen. Thus the nitrogen nucleus can be disintegrated either by the expulsion of an H atom of charge 1 or by the expulsion of an atom of mass 3 carrying 2 positive charges. Now helium is an atom of mass 4 carrying a nett nuclear charge of $+2$. Thus since the nett nuclear charge in an atom determines the number of external electrons and therefore the chemical nature of the atom the new atoms of mass 3 would have the same chemical nature as helium but would differ from it in mass. Such a relation is called "isotopic"—and the atoms of mass 3 are "isotopes" of helium.

I referred just now to the possibility that either the H nucleus or the α particle is asymmetrical. It has in fact been suggested by Rutherford that the α particle behaves in close collision as though it were a plate or disc of radius [illegible] $\times 10^{-[illegible]}$ cms. If such a structure collided with an H nucleus edge on, the distance between centres would be greater than 3×10^{-13} and the point charge law would hold according to the earlier experiments. If

however the conditions of velocity were adequate the approach might in many case be along the axis of the disc in which case the collision would be of quite a different nature and the H nucleus would be swept forwards Some extremely interesting calculations have been made by C G Darwin with the object of obtaining more definite information about the structure of the helium nucleus He discusses first of all what is the complete information which it is possible to obtain from experiments like Rutherford s and puts this information in the form of a relation between the velocity of the advancing α particle the angle of

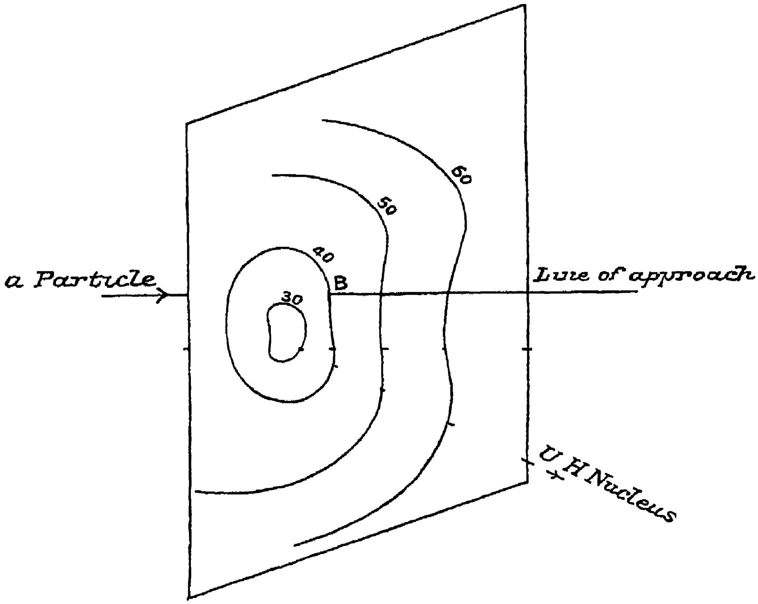

FIG 6

deflection and the number of scintillations of a given range produced by the projected hydrogen nuclei

The actual experiments are then analysed and expressed in the same terms The effect of collision of H nuclei with a series of model particles of different shapes is calculated and compared graphically with the reduced experimental results The method is based on what Darwin calls the *collision relation* a conception which I will try very briefly to describe

Suppose the particle is complex of any shape and has a point which may be called its centre Suppose the H nucleus which

I will call H is at rest Draw a plane through H perpendicular to the line of approach of the centre of the particle which I will call (fig 6)

H will be driven off at an angle of projection θ to this line of approach The angle of projection determines the velocity and therefore the range of H while from momentum and energy consideration $U = \frac{8}{5} V \cos\theta$ where U is the velocity of H and V is the initial velocity of

Consider both α and H to be oriented in a definite way I fixed and the direction of approach fixed Then if a stream of particles advances under these conditions the position of B is the only variable in the diagram and corresponding to each point like B there is an angle of projection θ Draw lines of constant θ and we get a *projection diagram* Its scale will be of the order of 10 cm Now take any area in the diagram less than a definite value θ_1 say Call this area P It will be a function of θ If and H have any orientation there will be one such diagram for each orientation and one value of P for each corresponding to each θ Let $\bar{P}$ be the average value of P Hence the number of H particles projected at angles less than $\theta = v = P \times$ (factors based on probability) Thus experiment can determine a relation between P θ and V if the α particles have all possible velocities This called the *collision relation*

Darwin next proceeds to find the collision relation which exists in the actual experiments of Rutherford

The observations were the ranges of the H nuclei if therefore we take these as having velocities equal to particles of the same range we can express the H ranges in term of velocities by applying Geiger s empirical law that the residual range at any point of the path is proportional to V^3 together with the equation $U = \frac{8}{5} V\cos\theta$

By considering the actual detailed conditions of the experiments an expression is deduced for the number of H scintillations occurring over an area A on the screen which corresponds to deflections less than a definite value of θ This number depends on the area A and hence depends on P

The actual relation is shown to be

$$= v \int P d\iota$$

where P is as I have said an unknown function of θ while ι and are known functions

By assuming that P a function of θ can be expanded by

Taylor's Theorem and writing $P = \pi p$ where p is a length on the diagram we get after integration

$$\frac{v}{v} = \pi p \quad (\theta - AV)$$

A and θ were calculated from Rutherford's experiments v and v are also known from the experiments Hence we can plot $\bar{p}$ against θ for different values of V

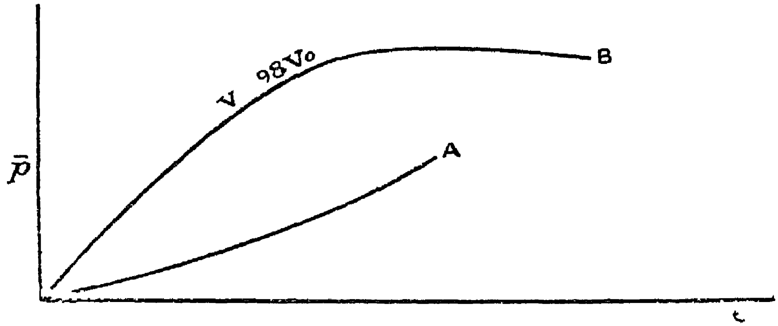

FIG 7

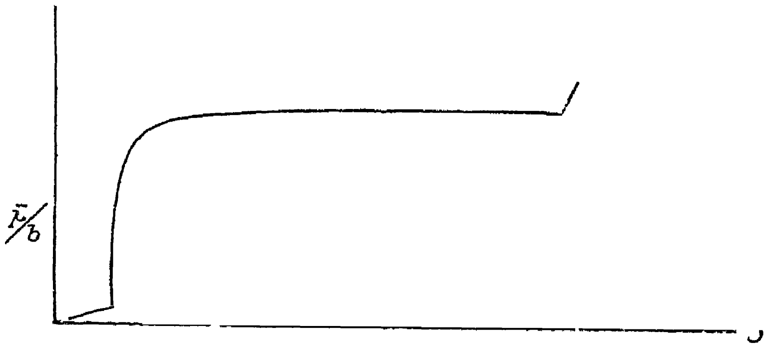

FIG 8

This gives a series of curves representing the results of Rutherford's measurements One of which is shown in curve B (fig 7)

The question now is what shape of a will produce a collision relation resembling these curves ?

Darwin assumes various models and calculates a relation for each kind—In fig 8 the quantity b is a constant

(1) Elastic sphere

The $\overline{p}\theta$ relation gives quite different curves from B

(2) Elastic plate (Fig 8)

Here the resemblance is much better The existence of a flat part implies a discontinuity of θ as $\overline{p}$ varies This is seen in the experimental curve (B fig 7) and the result is very remarkable as implying a discontinuity in the law of force between the nuclei

(3) A bipole (2 equal charges) arranged so that they lie in the plane in which the impact occurs

In some respects this case is better in some worse as regards agreement with the experimental diagram

The further development of this very interesting method awaits an increased accuracy in the experiments The latter are exceedingly difficult and trying owing to the continual counting of scintillations involved

Let us now consider the type of atom which the foregoing investigations of Rutherford would lead us to visualise

There would in a simple form of low atomic weight be a certain number of negative electrons grouped round a minute massive core whose nett charge equals numerically the sum of the negative charges outside it The core or nucleus itself may of course contain negative electrons but its balance of charge must be positive

In a simple atom possessing in its outer regions only a very few electrons the natural assumption is that stability is attained by the rotation of the electrons in orbits round the central core either in coplanar or in non coplanar rings either in circles or ellipses of various eccentricities When the complexity is greater and the atom contains a large number of electrons it is not so difficult perhaps to make out a case for stability by imagining the electrons at rest or oscillating in small circles on a sphere under the influence of their own mutual repulsions combined with the attraction of the central charge especially if the electron itself has magnetic properties as in the Ring type but in dealing with the simplest of all the hydrogen atom which there is good reason for believing consists of a single electron associated with a single positive charge of equal value it has not yet been possible on the ordinary view of the electron to conceive of any way in which the atom can be stable i e not collapse unless one imagines rotation of the electron round the centre

This conception leads to great difficulty in accounting for the observed magnetic properties of hydrogen and for the radiation emitted by the atom

In the case of more complex atoms where the nucleus itself is doubtless complex as indicated by Rutherford's work there is slight

ly more l\t tude for attempts to explain the magnetic cftects l ut the adiat on difficulty rema ns The nature of these difficı ltics and the deas that have been put forward to n eet the ll l d scus ed n the ı ext two lectuı es

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LECTURE III

A stage has been reached in this review of recent researches at which it is necessary for me to recall certain very revolutionary theoretical speculations which have developed during the past few years. It will be of advantage, I think, if I recapitulate the steps whereby these unorthodox results have come into being. They are largely connected with the theory of Radiation.

If a material body is placed in a constant temperature enclosure it finally comes to the temperature of the enclosure and there exists inside the latter a stream of radiation of all wave lengths passing in all directions whose amount[1] is independent of the material of the body or of the enclosure and depends only on the temperature and the wave length. This is called the *full radiation* for that temperature. It is the problem of radiation to find out how the energy density is distributed among the wave lengths.

Let the energy per unit volume for *unit range* of wave length near λ (say) be e, then for range $d\lambda$ (from λ to $\lambda + d\lambda$) the energy density is $e d\lambda$.

But e is a function of λ and θ only, therefore the energy density over any range is $\phi(\lambda, \theta)\, d\lambda$ and evidently

$$\frac{d}{dt}\phi(\lambda\theta) = E - A$$

the difference between rates of emission and absorption. In the steady state

$$\frac{d}{dt}\phi = 0 \text{ and } E = A$$

which we know to be true.

The question now arises, what is the mechanism of radiation and absorption?

The emission or absorption may be effected—

(1) by special resonators which account (say) for an amount of Emission E_P and Absorption A_J;

(2) by the truly free electrons in matter which account (say) for E_J and A_J;

(3) by orbital electrons or electrons closely associated with the atoms of matter emitting radiation as they are ejected from or return to the atom which account for E_P and A_J.

Hence
$$\frac{d\phi(\lambda\theta)}{dt} = (E_R - A_J) + (E_J - A_J) + (L_J - A_J) + \text{etc}$$

[1] Measured by the energy per unit volume or energy density.

But all the Es and As may contain ϕ since if we increase the energy at any wave length we expect to increase the absorption. So for the steady state if $A_T = a_T\phi$ we get

$$o = E_T - a_T\phi + E_I - a_T\phi + E_P - a_P\phi$$

$$\phi = \frac{E_R + E_I + E_P}{a_R + a_F + a_P}$$

Now $\frac{E_T}{R}$ $\frac{E_L}{a_D}$ $\frac{E_P}{a_P}$ will obviously vary from substance to substance.

But ϕ does *not* vary for different substances—full radiation is always the same. Hence by Algebra

$$\phi = \frac{E_R}{a_T} = \frac{E_I}{a_L} = \frac{E_P}{a_P}$$

$$= \frac{\phi E_R}{A_R} = \frac{\phi E_E}{A_F} = \frac{\phi E_P}{A_P}$$

$$A_R = E_R \quad A_I = E_L \quad A_P = E_P$$

i.e. each separate mechanism must be capable of establishing full radiation by itself separately.

Now let us examine the form of ϕ for each type of mechanism.

By resonators

Treat the resonator as a dynamical system in oscillation obeying the ordinary laws. It is possible to calculate the energy gained by it due to the action of an external impulse and hence to find the mean rate of absorption of energy and of emission of energy. Equating these values for the steady state it is found that the energy density D over a range $d\lambda$ is given by

$$D = \phi(\lambda\theta)d\lambda = 8\pi R\theta\lambda \quad d\lambda \tag{1}$$

By free electron

Treating the interaction of a light wave with a free electron it is clear that the motion of the electron will be compounded of—

(i) the undisturbed velocity of electron
(ii) harmonic oscillations set up by the wave.

The frequency of the light emitted in a particular direction can then be found by applying Doppler's Principle hence the average total radiation per unit time in terms of its separate frequencies can be obtained by integration. Thus for a number of waves simultaneously acting on the electron the average total radiation in terms of separate frequencies can be found and so we get the final partition of energy among the wave lengths.

For the steady state the partition of radiant energy must be unaltered by interaction with the electron

Hence $\phi(\lambda\theta)d\lambda$ the original partition can be found

It comes out the same as (1)

By orbital electrons

If the electrons are not free but are radiating by reason of acceleration imposed the same result (1) is arrived at

Now it is easily proved by the method of dimensions that in equation (1) the quantity $[8\pi\lambda \quad d\lambda]$ is the number of vibrations per unit volume of the medium which have wave lengths between

$$\lambda \text{ and } \lambda + d\lambda$$

Hence $[R\theta]$ is the *average energy of each vibration*

These same results follow from much more general considerations regarding the partition of energy between matter and ether—namely the theory of equipartition of energy

Hence from all points of view and employing every conceivable mechanism for emission or absorption provided the reasoning is based on the principles and processes of ordinary Newtonian dynamics we are led inevitably to the same result that the energy density of full radiation is $8\pi R\theta\lambda \quad d\lambda$ for the steady state

If now this expression is integrated between $\lambda = 0$ and $\lambda = \infty$ we find that the total energy for all wave lengths is infinite But this is not true since we know that the energy in matter is *not all* dissipated into radiation in the ether

For instance if the energy corresponding to different wave lengths in the solar spectrum (ultra violet to infra red) is measured experimently and plotted against the wave lengths the curve reaches a maximum in the visible portion of the spectrum and does not increase indefinitely in the region of short waves (See fig 9) Similar experimental results are obtained from full radiation produced in constant temperature enclosures in the laboratory

Thus something is wrong The Quantum theory has been invented to account for the observed facts since Newtonian dynamics is apparently incapable of doing so

Let us now consider one way in which the idea of an energy quantum has arisen and how it has served to reconcile the discrepancy just referred to

The probability of a system at absolute temperature θ

having any particular energy is well known to be $Ae^{-\frac{}{R\theta}}$ where R is the gas constant

The probability of the system having energy 2 is $Ae^{-\frac{}{R}}$ and of its having zero energy is A

Now if m is the number of vibrations having energy m the number having energy 2 and m the number having zero energy then we have

$$\frac{m}{n}=\frac{\text{Probability of system having energy}}{\text{Probability of its having zero energy}}$$

i e $$\frac{m}{m}=\frac{Ae^{-\overline{R\theta}}}{A}$$

or $$m - m e^{-\overline{R\theta}}$$

also $$m_2 = m e^{-\overline{R\theta}}$$

If there are M vibrations and if the energy can only be selected or can only exist in bundles or quanta of value 2 3 etc

then $$M = m\left(1 + e^{-\overline{R\theta}} + e^{-\frac{2}{\overline{R}}} + e^{-\frac{3}{\overline{R\theta}}} + \right)$$

$$=\frac{m}{1-e^{-/R\theta}}$$

Now the total energy of all the vibrations is

$$m \quad + m \quad 2 + m_3 \quad 3 + \text{etc}$$

$$= m e^{-\overline{R\theta}} \quad + m e^{-\frac{2}{\overline{R\theta}}} 2 +$$

$$=\frac{M}{e^{/R\theta} - 1}$$

If we take vibrations only between λ and $\lambda + d\lambda$ per unit vol of ether $M = 8\pi\lambda^{-} d\lambda$ therefore the total energy per unit volume D is given by

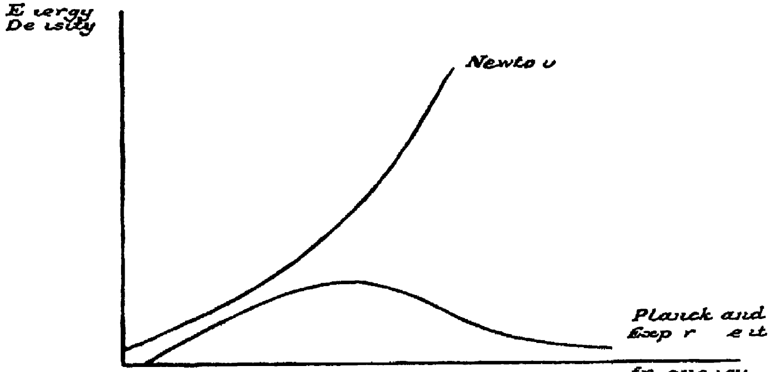
$$D = 8\pi\lambda^{-} d\lambda \frac{}{e^{R\theta} - 1} \tag{2}$$

If $e=0$ the energy can have any value however small i e the bundles are infinitely small

So the total energy per unit vol $= 8\pi\lambda^{-4} d\lambda\ R\theta$ which as we have seen is *not* true experimentally If $\neq 0$ then from (2)

$$D = 8\pi\ R\theta\lambda \quad d\lambda \frac{\overline{R\theta}}{e^{\overline{R}} - 1}$$

If in addition $=h\nu$ where h is a constant usually known as Planck's Constant and is the frequency i e *the quantum is proportional to the frequency* we get Planck's formula for the radiation



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density *which agree very well indeed with actual measurements* (see fig 9) From experiment $h=6\ 6\times 10$ ergs sec also for the D line of sodium $=5\times 10$

$$=h = 3\ 3\times 10 \quad \text{ergs}$$

Now Poincare has shown that

No system of resonators or any other mechanism can possibly lead to Planck's law except one in which $=h$ is satisfied indeed it is shown definitely and conclusively that the mere fact that the total radiation at a finite temperature is finite require that the ultimate motion should be in some way discontinuous

It is important to remember that there is no indication in the previous arguments as to whether these quanta of energy really suggest an atomicity of energy itself or whether they imply that the selection of energy for absorption by matter occurs in fixed limited parcels

This last alternative forms one of the outstanding problems t the day

Consider the expression

$$\frac{\text{value of an energy bundle}}{\text{average energy of a vibration}}=\frac{h\nu}{R\theta}=x \quad (\text{say})$$

Then $=h\left(\frac{1}{I\ \theta/\nu}\right)=I\left(\frac{1}{R\theta}\right)$ where τ is the time period hence h

has the dimensions of Action and Planck's formula becomes

$$D = 8\pi R\theta\lambda^{-4} d\lambda \frac{x}{e - 1}$$

Now when x is very large there are very few quanta in the vibration (of which $R\theta$ is the average energy) and Planck's law holds; when x is very small there are very *many* quanta in the vibration ($R\theta$ large) and the ordinary Newton Rayleigh Jeans law

$$D = 8\pi R\theta\lambda^{-4}d\lambda$$

holds.

So the Newtonian laws *begin to fail* when the average energy does not contain a great number of quanta.

But x can be large by

(i) being large (quanta large)

or (ii) θ being small (energy small and few quanta).

Similarly Newtonian laws hold (or x is small) when $R\theta/\nu$ is great compared with h, i.e. Action $R\theta\tau$ great compared with 6.6×10 erg sec. Thus we should expect Newtonian laws to *fail* either when θ is very low or ν very high and Action very small.

This is exactly what is found by experiment. It is well known that the atomic heats of solids approach a constant value 6 provided the temperature is sufficiently high, but that at low temperatures the atomic heat decreases rapidly.

Now Newtonian dynamics, assuming as it must that the total energy per unit volume of the material is independent of the nature of the vibrations of its atoms, demands constancy of value for the atomic heat at *all* temperatures. There is thus a vital discrepancy between theory and experiment. The discrepancy has been met by Debye, who assumes that the average energy of a vibration depends on the frequency of that vibration, thus introducing once more the idea of the quantum of energy. The deductions from Debye's theory agree admirably with experiment.

Another instance which supports the conception of the quantum is provided by the photoelectric effect.

When ultra violet light falls on a negatively charged metal plate no photoelectric emission of electrons occurs unless the frequency of the radiation is greater than a certain limiting value. Moreover the maximum velocity possessed by the electrons given off depends for any metal only on frequency of the incident light; in addition the energy absorbed by an electron in emerging from the atom[1] is (within experimental limits) precisely one quantum h, where h is Planck's constant 6.6×10 erg sec.

Nor are these the only instances in which energy is dealt with

[1] Apart from any additional energy required during emergence from the plate.

by matter on this curious selective principle. The kinetic energy E of an electron in a cathode stream impinging on matter gives rise to X rays of frequency ν only if the energy is related to the frequency according to this same equation

$$E = h\nu \tag{3}$$

Another example involves the collision of electrons with the atoms of gases.

The latter are stimulated to emit their so called "single line" or "resonance" spectra only by electrons possessing more than a certain fixed amount of energy; if the electron is not moving fast enough the particular radiation is not produced. The proved relation between the electron energy E and the frequency ν of the "resonance" line produced by the collision is again the same as equation (3). Lastly must be mentioned the Bohr theory of the hydrogen atom which by an application of the quantum hypothesis accounts for the spectral series of hydrogen. This theory is dealt with in lecture V.

In view of all these discoveries the general trend of thought is towards the conception that the atom possesses some mechanism for absorption and emission of energy by jumps. Any mechanism which may be imagined to account for this will be welcomed as an aid to progress even though the form of that mechanism may eventually have to be discarded as lacking generality. Possibly, as W. Peddie has remarked, any model of which we may conceive will leave part of the essential mechanism undescribed.

I will conclude with a brief reference to some very important results quite recently published by Prof. E. T. Whittaker in a paper "On the Quantum Mechanism in the Atom." Therein he suggests a model which illustrates a possible method of interchange of energy between atom and colliding electrons which helps to a realisation of the kind of physical process which may be involved in quantum absorption and emission.

It is first pointed out that the electric field in the neighbourhood of an atom is not permanent (since the atom is electrically neutral under ordinary conditions) but is evoked by the approach of the electron.

Correspondingly the electron as it approaches the atom induces within the atom a magnetic current, the magnetic analogue of an electric current.

The mechanism which is assumed to exist in the atom and to give rise to these effects is a series of bar magnets with like poles at the origin and free to rotate (like the spokes of a rimless wheel) in one plane. When such a system is rotating it sets up an electric field which affects an electron approaching along the axis, while the magnetic poles revolving in a circle constitute the magnetic current. The two dynamical differential equations

(Newtonian dynamics) which express the interaction between the circular magnetic current and the advancing electron are very simple and easily obtained

On integration they provide an expression for the angular velocity of the magnetic system and a conservation of energy equation from which it appears that as the electron comes into the neighbourhood of the magnetic structure its velocity diminishes and its kinetic energy is expended in setting the structure into rotation If all the electron s energy is used up in this way before it reaches the centre it returns on its path in fact an elastic impact has occurred

It is proved that if u the initial kinetic energy of the electron is greater than U wher

$$U=\frac{2e\ M}{A} \qquad \text{I}$$

and M depends in the magnetic moments of the magnets while A is a constant the electron passes completely through the mechanism and away from its influence on the other side giving up to the structure during its passage exactly the amount U of energy and retaining the rest The absorbed energy appears as magnetic current in the structure also if ω i the final value of the angular velocity of the structure after the electron has passed away to infinity we have

$$\omega=\frac{2eM}{A} \qquad (2)$$

Hence from (1)

$$U=eM\omega \qquad (3)$$

Proceeding to the problem of the transformation of energy into radiant form by the mechanism within the atom Whittaker shows that the magnetic current is equivalent to an electric shell or what is the same thing a charged electric condenser

By combining the expression for the charge or this atomic condenser of capacity C with equation (3) we get

$$C=\frac{e}{2U} \qquad (4)$$

which connects the capacity with the energy absorbed from the bombarding electron

When such a condenser is discharged clearly C is related to the inductance L and the frequency by the well known equation

$$=\frac{1}{2\pi\sqrt{LC}} \qquad (5)$$

provided the discharge is oscillatory

It is then shown that the expression $e\sqrt{\frac{L}{C}}$ is a natural con

st ı t l ıv ng the d mens oı s of Act oı Writing $2\sqrt{\frac{L}{C}}=\frac{I}{\pi}$ an l co nb ıng witl equations (4) nd (5) ve l ave

$$U=h$$

l cl ıs precisely Pl ınck s relation a ıd ı volves no departuıe fıo n the class cal dyn ım cs

Thıs ıs Wh ttake po nts out the model reproduces by ts ct o the l eh ıv ou of the ctual ıto n ıs found expe ment lly

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LECTURE IV

One of the large outstanding problems of physics to-day is the explanation of magnetism. Perhaps less advance has been made in this direction than in any other, and I believe that magnetic phenomena have not received their due proportion of attention in recent years.

I propose in this lecture to consider a few special points connected with the magnetic behaviour of matter, and I will lead up to what I have to say by reminding you very briefly of the ordinary theory of dia- and paramagnetism.

Imagine an atom containing electrons which describe circular orbits about an attractive centre.

Each orbit with its revolving charge is magnetically equivalent to a small magnet placed at the centre of the orbit, and possesses therefore a magnetic moment whose magnitude can be shown to depend on the angular velocity of the electron and on the area of the orbit.

There may be several electronic orbits in any particular atom or molecule; consequently the structure as a whole would be expected in general to possess a resultant magnetic moment, which of course for special arrangements of the orbits might be zero. (See fig. 11.)

Let us consider first of all the effect of an external magnetic field on an atom or molecule of zero resultant magnetic moment.

Each of the separate electron orbits will be affected by the field, and in this way the angular velocity of the electrons will be changed, but not the area of the orbits;[1] consequently a change in the magnetic moments of the orbits results, and this change is always such as to *decrease* their existing magnetic moments. But since there is no magnetic axis any turning of the separate orbit planes has no effect in turning the atom as a whole. Now in any substance containing a multitude of atoms the sum of the changes in magnetic moment thus produced per unit volume divided by the strength of the external field is the susceptibility of the material.

Thus the susceptibility can be found from first principles in terms of the orbit areas, the number of atoms of a particular kind in unit volume, and the constants e and m. Moreover, since the effect of the external field is always to *diminish* the magnetic

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[1] Provided the law of inverse squares holds for distances comparable with the atomic radius.

moments of the individual electron orbits the susceptibility deduced is diamagnetic

Now consider the effect of an external field on a type of atom which possesses a resultant magnetic moment not zero

The diamagnetic susceptiblity exists as in the previous case for each individual orbit will have its angular velocity slightly changed but superposed on this is the action of the field on the resultant magnetic moment of the atom as a whole The magnetic axis of the atom system will endeavour to set parallel to and in the same direction as the applied field i e in the position of minimum potential energy It will be restrained from setting quite parallel (*a*) by those collisions with other atoms which are associated with the heat energy of the material (*b*) by (in the case of solids) magnetic or electrostatic forces exerted by neighbouring atoms

The same reasoning applies if we deal with molecules instead of atoms Matter built up of atoms or molecules of this kind possesses a positive value for the susceptibility for the magnetic axis of the atom sets in the *same* direction as the applied field therefore the material is paramagnetic

It appears at first sight that diamagnetic properties on this theory should be independent of temperature of change of state and of chemical action since the *atom* electron orbits alone are concerned But this is not strictly true experimentally Paramagnetic properties on the other hand should be dependent on the temperature since the kinetic energy of the molecules plays an important part in adjusting the value of the susceptibility

It can in fact easily be proved by thermodynamic and other reasoning and it has also been verified by experiment that the para magnetic susceptibility $\chi_P = \frac{A}{T}$ where T is the absolute temperature and A is Curie's constant

In the case of the few solids which exhibit ferromagnetism the magnetic behaviour is doubtless enormously complicated by the close proximity of neighbouring molecules but in attempting to account for both ferro and paramagnetism the possibility of the existence in all paramagnetic molecules of special structures giving rise to *large local magnetic fields* must always be borne in mind Moreover there is a strong probability that magnetic susceptibility in all materials is a resultant or balance between para and diamagnetic quality In some materials paramagnetism preponderates in others diamagnetism preponderates the resultant effect determines the magnetic property observed I shall return shortly to the question of large local fields in the atom

Meanwhile let us consider Langevin's theory of a paramag-

netic gas which is founded on the kinetic theory of gases and lead fairly simply to the equations

$$\frac{I}{I} = \frac{\cosh a}{\sinh a} - \frac{1}{a} \qquad a = \frac{MH}{RT} \tag{1}$$

where I is the maximum possible intensity (all the magnetic axes parallel to the external field)

M the resultant magnetic moment of a molecule

H the applied field

R the gas constant applied to a single molecule

T the absolute temperature

One of the important applications of these equations which bears on recent work to which I want to call your attention was made by Weiss His object is to elucidate the phenomenon of ferromagnetism in which since solids alone exhibit these properties it is essential to take account of the influence of neighbouring molecules As is well known to many of you Weiss assumes that each molecule is subject to the influence of a molecular local magnetic field H_2 which so long as the material is at a temperature below its critical point is independent of the external magnetising field H_1 The local field may be caused by special structures in the atom of which at present we have no direct evidence but in any case the device of the Weiss hypothetical local field replaces the effect of molecular aggregation below the critical point and enables that effect to be neglected in the calculation

Thus the total field to which the material is subject is H (the external field) $+ H$ (the local molecular field)

$$= H + \lambda I$$

since H is proportional to the intensity of magnetisation produced by itself λ is a constant Hence regarding equations (1) as applying

we have $$a = \frac{M(H_1 + \lambda I)}{RT}$$

Now near the critical temperature where the ferromagnetic susceptibility vanishes and the material becomes para magnetic a is small and equation (1) reduces to $\frac{I}{I} = \frac{a}{3}$ so that the critical temperature T is determined by

$$T = \frac{\lambda I M}{3R}$$

whence $$(T - T)I = \frac{H T}{\lambda} \tag{2}$$

Hence if H_1 is constant I T curves are hyperbolas near the Curie point which is true experimentally

From equation (2) and a knowledge of the magnetic behaviour near the Curie point it is possible to find λ and therefore $I\lambda$ which is H the local molecular field

Its value comes out

for	Iron	3.5×10 gauss
	Nickel	6.4×10^6
	Magnetite	1.4×10^6

I would direct your special attention to the very large value of the order 10^7 gauss obtained for this hypothetical local molecular field

It is at once suggestive of some mechanism in the atom which produces a large field in its *immediate* neighbourhood— at least in the case of ferromagnetic matter

There is one other aspect of Weiss theory to which I will refer

If we deal with the magnetic moment I of the molecules themselves and if you remember that near or above the critical temperature $\frac{I}{I_0} = \frac{a}{3}$

we have $$I = \frac{M I_0 H_2}{3RT} = \frac{I_0 N M H}{3NRT} = \frac{I_0^2 H}{3NRT}$$

where N is the number of magnetic molecules per gram whence if χ is the molecular susceptibility $\left(=\frac{I}{H}\right)$ per unit mass and if we remember that $MN = I_0$

$$\chi = \frac{I_0^2}{3RTN} = \frac{M\chi}{3RT} = \frac{A}{T} \text{ where } A = \frac{I_0^2}{3RN}$$

the Curie constant and RN is the gas constant

On plotting experimental values of $1/\chi$ against T the graph is found not to be a single straight line but to be made up of bits of straight lines (fig 10) Hence the constant A must vary If A is regarded as varying in respect of T we can find from the curve the different values of I which correspond to different temperature intervals These are found to be exactly in the ratio $4m$ $5m$ $6m$ $8m$ $10m$ where m is a constant

Since the values of I for other ferromagnetic substances are also multiples of m it is inferred that the magnetic moments of the molecules are multiples of a common universal magnetic element which Weiss calls the magneton Its moment is 18.54×10 C G S electro magnetic units

The magnetic moment of the electron orbit on the Bohr Rutherford theory (see Lecture 5) is an integral multiple of a constant whose value is five times that of Weiss magneton i e

92 7 × 10 electromagnetic units while the angular momentum of the ring electron is about twice this or 200 × 10 electromagnetic units

It should be remembered that if I is constant and N varies the implication would be that polymerisation occurs at different temperatures but the ratios of the different values of N are not so simple as in the case of I

An examination of one of Weiss curves (fig 10) indicates the strength or weakness of the evidence on which this theory hangs one would be less inclined to accept the idea of the magneton were there not other lines of argument which lead to similar conclusions

In a recent series of papers of great interest Oxley approaches the question from a somewhat similar standpoint but considers the case of a diamagnetic crystalline substance which melts to a

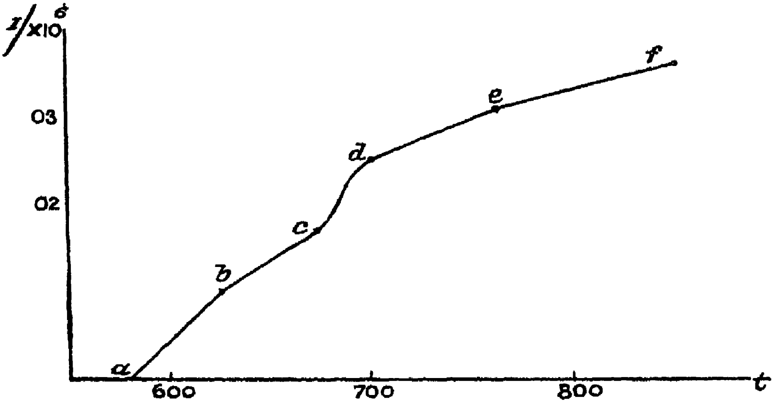


FIG 10

diamagnetic liquid Many such substances are known by experiment to show a marked change of susceptibility on passing to the liquid form Working from Langevin s equations of motion for an electron in a magnetic field it is assumed that a local molecular field H exists in each molecule and that the field makes itself felt when the liquid crystallises as a change of susceptibility Oxley replaces in fact the influence of neighbouring molecules by assuming their effect equivalent to that of a local magnetic field The equation which expresses the change of susceptibility is

$$\frac{\partial\chi}{\chi} = \left(1 \pm \frac{e\tau_l H}{4\pi m}\right)\left(1 \mp \frac{e\ H}{4\ m}\right) - 1$$

where τ_l is the time period of the electron in its orbit when in the liquid or gaseous condition i e not under the influence of H due

(*d*) The nuclear system of the molecule may be itself in rotation This possibility has been considered by K Honda and Okubo who worked on Bohr s model It is proved that if the axis of rotation of the molecule as a whole i e the nuclear system is perpendicular to the magnetic axis the resultant magnetic polarity is diamagnetic The velocity of rotation of the nuclei is much smaller than that of the external or valency electrons Taking the observed values of χ for Hydrogen the frequency deduced is $1\ 04 \times 10^{14}$ which corresponds to infra red radiation

(*e*) Crehore has proposed a model for the hydrogen *atom* in which the nucleus is complex and consists of two protons and one electron giving a nett nuclear charge of $+e$ This system together with an additional negative electron is in rotation about a common axis The magnetic properties of such an atom have not been fully examined so far as I am aware

In connection with the magnetic properties of more complex molecules it is worth while recalling the theory of Ritz which was extremely successful in accounting not only for Balmer s series but for many other spectral series and for the positive and negative Zeemann effect Ritz postulates a magnetic field peculiar to the atom of definite strength whose axis s along the axis of the valency electron s orbit to which it is rigidly attached The origin of the field is not dealt with by Ritz in any detail but it may be conceived of as being due to a special rotating electron whose orbit is smaller than that of the valency electron It has indeed been identified by Zeemann with Weiss magneton In order to account for the magnetic resolution of certain spectral lines Ritz assumes a precessional movement of the magneton and suggests as an explanation that this movement may be caused by *free* electrons in the material projected into the intense magnetic field near the atom If an electron behaved thus it would describe a helix round the axis of the field its *electrostatic* effect on the charged magneton in the atom would be to start precessional movement in the *opposite* direction to its own

The Bohr model atom built up as it is by a combination of the experimental results of Rutherford with the concepts of the quantum or unit of *action* and accounting as it does with great perfection for the Balmer series of hydrogen and for other atomic series discovered in the stars is not to be discarded lightly Nevertheless if it is to represent even an approximation to reality it ought obviously to account for the facts of magnetism at least as successfully as it accounts for those for radiation As things are at present the Bohr atom and molecule without modification do

not do so and I think it is clear that physicists must face one or other of the alternatives just enumerated.

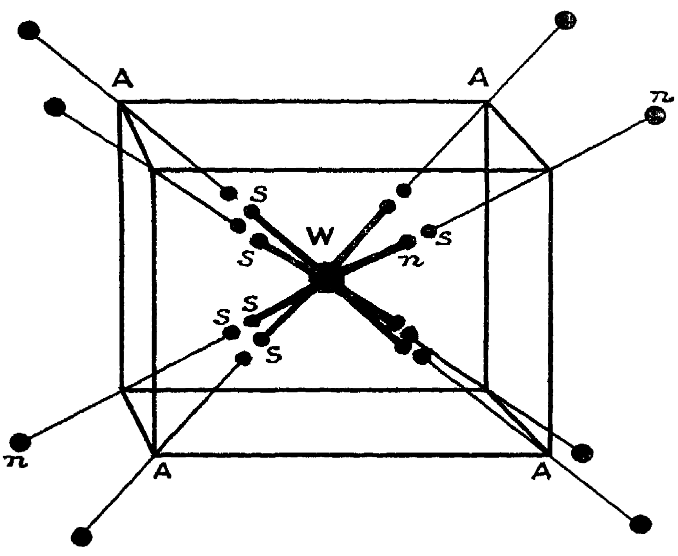
So far the general trend of research leads to a belief in the elementary magnetic unit. The question arises what are its dimensions? Is it of the order of magnitude of the atomic group such as would form the unit of architecture in crystal structure, or is it of atomic dimensions, or is it sub-atomic, that is, of dimensions somewhat larger than the nucleus itself but smaller than the distance between the nucleus and the nearest valency electron? A certain amount of direct evidence has been obtained recently by A. H. Compton and Rognley on these points. They find that the Laue diffraction pattern obtained through a ferromagnetic crystal is unaffected on magnetisation. They also show that the intensity of a beam of X-rays reflected from a crystal face of magnetite does not change on magnetisation of the crystal. If magnetisation shifted the atom as a whole including the valency electron rings it is claimed that the reflected X-rays would be changed in intensity. The conclusion is that the elementary magnet is really sub-atomic and is associated perhaps with the nucleus, perhaps with the ring electron of Parson.

Experiments on scattering of α particles in magnetic matter should obviously be of great importance in connection with the determination of the existence of special structures in the magnetic atom.

Some very interesting results have recently been obtained by Sir Alfred Ewing which throw fresh light on the process of magnetism in a ferromagnetic solid. Ewing's original magnetic model, it will be remembered, regarded the molecule as being the magnetic element. In the light of recent work he now conceives the magnetic element to reside in the atom and to be distinct from those electrons which are immediately responsible for chemical action — the so-called valency electrons. The Weber element, as the ultimate magnetic entity may be termed, is possibly an electron orbit associated with the nucleus; in any case it is supposed capable of rotating relatively to the atom as a whole (and independently of it) under the influence of an applied field. The valency rings, although fixed relatively to neighbouring atoms, nevertheless exert an electro-magnetic control on the Weber element as it turns, which gives the latter a certain feeble stability. When an external field is applied, at first (for very small fields) the Weber element rotates to a very small amount and the rotation is reversible, i.e. if the field is removed the element returns to equilibrium. For larger fields instability occurs and the Weber element swings over into a new equilibrium position governed by geometrical factors, by the control of the other parts of the atom and by the value

of the external field itself During this process which is not i versible there is of course dissipat on of energy

These ideas are illustrated by models of which one is shown diagrammatically in fig 13 4 *A A A* are bar magnets repr senting the valency electrons at the corners of a cube which thus exhibits the cubic ferromagnetic crystalline structure The space lattice of iron is the centred cube and it is imagin d that a corre sponding grouping of the valency electrons exists in the atom itself The central portion *W* which is supported on a needle point (not shown) represents the moveable Weber element It consists in the model of 4 bar magnets lying along the diagonals of the cube with



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their poles as shown thus *W* takes up the position of equilibrium indicated in the figure when there is no external field There is some stability in this position and if an uniform magnetic field acts on the atom *W* at first is deflected reversibly but soon when the field is slightly increased tumbles over into a new position of equilibrium It is evident that the Weber element possesses a magnetic moment and that the axis will turn (subject to sudden unstable jumps) into line with the applied field as the latter is increased By calculation based on the model Ewing has obtained results not only in qualitative but in quantitative agreement with the known phenomena of magnetic induction in iron and nickel In fact

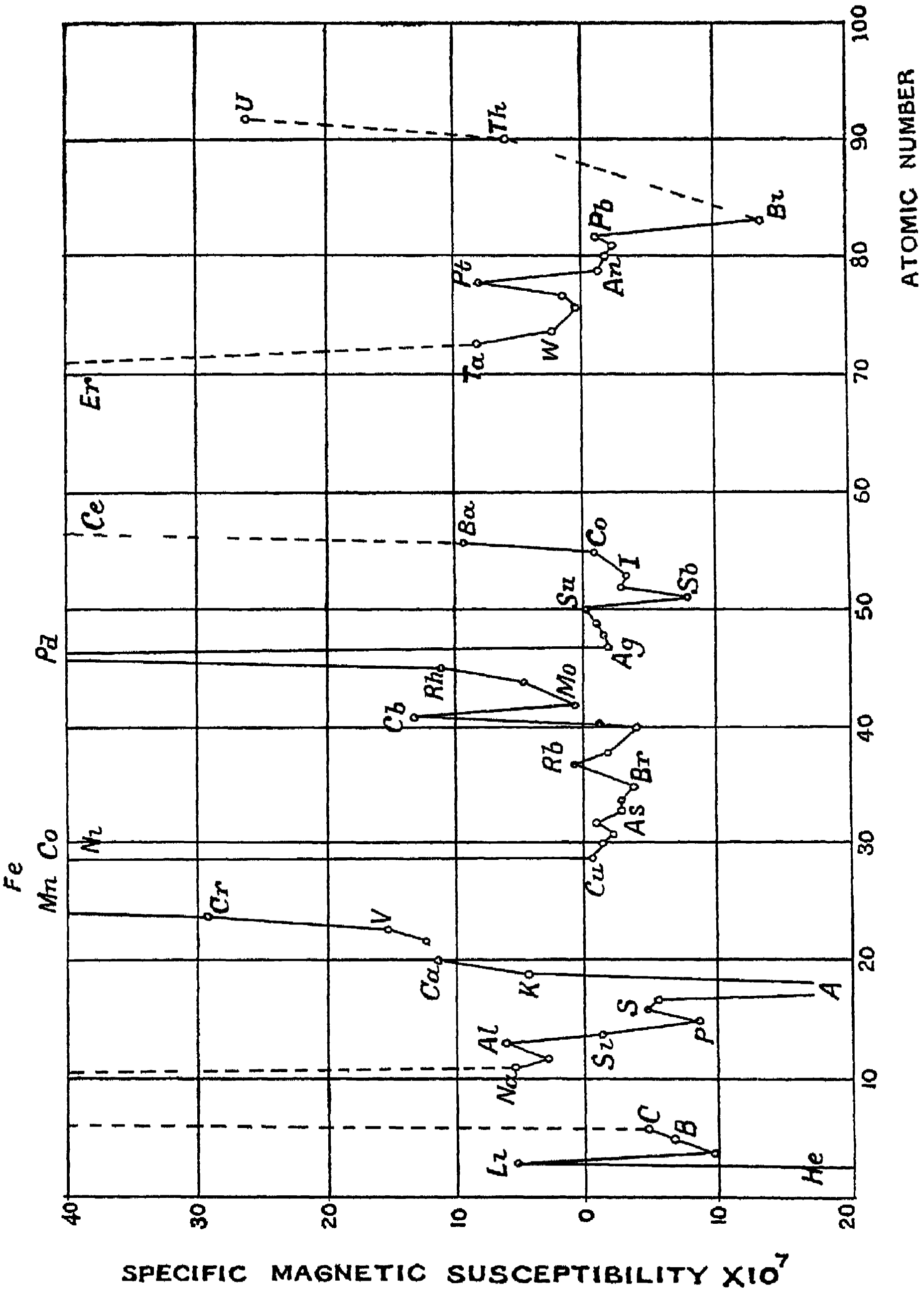
SPECIFIC MAGNETIC SUSCEPTIBILITY X10^7
ATOMIC NUMBER
40 30 20 10 0 10 20
10 20 30 40 50 60 70 80 90 100
Li He C B Na Al Si P S A K Ca V Cr Mn Fe Co Ni Cu As Br Rb Cb Mo Rh Pd Ag Sn Sb I Cs Ba Ce Er Ta W Pt Au Pb Bi Th U

Fig. 1

complete H B curves have been reproduced with numerical values for H and B and for the coercive force in excellent agreement with values for iron It will be noticed that the conception of a structure associated with the atom which passes from one position of stable equilibrium to another with dissipation of energy in the manner indicated at once suggests the process referred to by Whittaker and described at the end of Lecture III Suppose for example we imagine the Weber element to have no magnetic moment This could be attained by arranging all the north poles in the hub We should then have a picture of an atom of a ferromagnetic element as it might be supposed to exist above the critical temperature If now an electron approaches the atom from outside W would be deflected and if the energy of the bombarding electron is just great enough all the energy would be absorbed by the atom and W would pass to another position of equilibrium During the process it would oscillate and radiation would be emitted the energy associated with which would bear a precise relation to the initial energy of the bombarding electron As Ewing points out however when a single line spectrum is produced it is perhaps more probable that the bombarding electron merely sets the Weber element oscillating about its original equilibrium position without producing displacement to a fresh stable equilibrium position The quantum of radiation on this idea would be determined by the amount of energy given up to the atom by an electron which passed completely through the atom The photoelectric effect would be caused by the Weber element being set into resonant oscillation by light of the correct period when sufficient amplitude had been attained an electron would be emitted depriving the atom of a quantum of energy by reason of the angular impulse exerted on the atom stopping the oscillation

When we come to consider the way in which the magnetic properties of the elements depend on the atomic weight [or the atomic number] some indirect evidence is obtained that either the electron orbits of the more complex atoms are in different planes or that the electrons in certain orbits are rotating in a contrary sense to the remainder Otherwise there would be steadily increasing magnetic susceptibility as the complexity of the element increased That this is not the case is shown quite definitely in fig 14[1] in which the specific susceptibility is plotted against the atomic numbers of the elements

[1] Taken from a paper by Harkins and Hall See Reference below

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LECTURE V

The chemical evidence Rutherford s experiments and many other converging lines of thought render it certain that the hydrogen molecule is the simplest form of matter which we can directly observe in our laboratories[1] It seems natural therefore to examine in some detail what kind of model hydrogen atom conforming to the limits made clear by α ray scattering experiment best satisfies the observed spectral and magnetic phenomena Later on in logical advance it will be necessary to pay attention to the vital question of association of such model atom to form molecules thus we shall be led through the more complex association of atoms of different kinds to the supreme test of any atomic theory the necessity of accounting for chemical valency Bearing in mind the fundamental experiments on α ray scattering I propose in the first place to review briefly the more important hydrogen atom models which have been proposed of recent years Since atomic hydrogen has not yet been utilised for experiment at least on the earth our direct knowledge of the behaviour spectral or magnetic of gas composed of dissociated atoms is nil we can only infer indirectly that certain observed spectral series are really due to the atom as distinct from the molecule Consequently any apparent success in atom synthesis will be discounted if at the same time the model proposed fails satisfactorily to combine with its own kind and produce a molecule Evidence which I hope to bring forward in the final lecture together with that afforded by the Rutherford experiments indicates that the hydrogen atom is a structure in which a minute massive nucleus positively charged is in association with a single negative electron and that the net positive charge on the nucleus is equal to e the charge on the negative electron There is as yet no conclusive evidence that the H nucleus is really the positive electron or proton it may be a more elaborate structure Neither is there so far as α ray scattering experiments go any direct evidence as to whether the negative electron is in dynamic equilibrium with the nucleus that is rotating orbitally round it or whether the negative electron is held in static equilibrium

It is realised however that in the present state of our knowledge regarding the forces inside the atom an orbital or dynamic equilibrium of some kind must be postulated otherwise the negative electron would fall into the nucleus By assuming a

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[1] It is only quite recently that atomic hydrogen has apparently been isolated by R W Wood

special structure for the negative electron itself the difficulty may to some extent be met and this possibility will be referred to again later but with the ordinary conception of the negative electron it would appear that in such a simple structure as the hydrogen atom we are faced with a limitation imposing some kind of orbital motion with which we do not necessarily meet when dealing with more complex atoms The latter with their large complement of electrons might possibly be in a condition of static equilibrium it is impossible to see how the hydrogen atom with its single electron can be

With these general considerations in mind let us see to what extent a hydrogen atom consisting of a positive nucleus and a negative electron in orbital motion round it fits the observed facts

It must be admitted at once that such a system under Newtonian laws does not fit the facts at all An electron revolving in an orbit is subject to transverse acceleration and therefore must radiate energy as was noted in the first lecture As it radiates the total energy of the atom changes and therefore the frequency of the radiation Eventually as surely as though it were not in orbital rotation the electron would fall into the central nucleus Thus a gas made up of atoms of this kind even if the latter were associated into molecules would under suitable stimulus emit radiation of all possible frequencies and would show a continuous spectrum and *not* sharp lines as are actually observed

Sharp lines demand either a constant radius for the electron orbit or that the radius should have a number of *possible stable values to which it could jump instantaneously*

Now no possible application of Newtonian dynamics can account for discontinuities of this nature In order to reconcile the difficulty Bohr in 1913 made the suggestion that the angular momentum of the electron is always equal to $\tau \frac{h}{2\pi}$ where τ is an integer (i.e. 1 2 3 etc.) and h is Planck's constant Thus the assumption of Bohr amounts to a statement that if the angular momentum of the atom changes it can only do so by jumps That is the angular momentum of electron orbits can have the value

$$1 \times \frac{h}{2\pi} \text{ or } 2 \times \frac{h}{2\pi} \text{ or } 3 \times \frac{h}{2\pi} \quad \text{etc}$$

If W is the negative energy of an orbit then from the conditions for a circular orbit

$$W = \frac{1}{2}\frac{eE}{a}$$

where e is the charge on the negative electron E is the net charge on the positive nucleus and a is the orbit radius Also if Ω is the

angular momentum of the orbit m the mass of the negative electron and its angular velocity we have

$$\Omega = 2\pi m\ a$$
$$= \frac{2\pi\ m\ \ a}{\pi}$$
$$= \frac{m\ (2\pi a\ \ )}{\pi\omega}$$
$$= \frac{\text{the kinetic energy}}{\pi\omega}$$
$$= \frac{W}{\pi\omega}$$

If the negative energy of the orbit is calculated it is found that on Bohr s assumption

$$W = \frac{2\pi\ me\ E}{\tau\ h}$$
$$a = \frac{h}{4\ \ meE}$$
$$= \frac{4\pi\ meE}{h}$$

Thu by giving integral values to we get perfectly definite values for W a or ω

For example a must have the values $1 \times \frac{h}{4\ \ meF}$ or $4 \times$ this or $9 \times$ this and so on

Thus there can be hydrogen atoms of each of these sizes

If $\tau = 1$ we find the diameter of the hydrogen atom a is 10^{-8} cm which agrees with the accepted value Bohr assumes that on occasions a radius may shrink from a value given by $\tau =$ to a value given by $\tau =$ When this happens the change of energy

$$\delta W = \frac{2\pi\ me\ E}{h^2}\left[\frac{1}{\tau^2} - \frac{1}{\tau^2}\right]$$

and this is supposed by an additional assumption to be the equivalent of *absolutely monochromatic radiation and exactly equal to 1 quantum of energy* which is emitted from the atom during the change of orbit

Thus $$\delta W = \ = h\ = \frac{2\pi\ me\ E}{h}\left[\frac{1}{\ } - \frac{1}{\ }\right]$$

whence $$- N\left(\frac{1}{\ } - \frac{1}{\ }\right)$$

There will thus be various possible frequencies in the emitted radiation

There will be a series $=1$ whose lines will be given by $=2\ 3\ 4$ etc and a series $=2$ whose lines will be given $\tau=3\ 4\ 5$ etc For hydrogen where $E-e$ and taking $\tau=2$

we have $$= N\left[\frac{1}{4}-\frac{1}{3\ 4\ \text{or}\ 5}\right]$$

which very exactly expresses the frequencies of the lines in Balmer's series N is Rydberg's constant its calculated value is $3\ 26\times 10^{15}$ while the value obtained by experiment is $3\ {-}6\times 10$

Other series corresponding to $\tau\ 1=$ and $\tau=3$ have been discovered

There is evidence that in the stars there may be hydrogen atoms of dimensions 1000 times that of the normal atom

It is interesting to note that on Newtonian dynamics Rydberg's constant (N) which appears to be a universal constant cannot be built up of the universal constants e m and V the velocity of light

But on the quantum theory $N \quad \frac{-\ ,}{h}$ s h s also available and it is possible to build up N entirely in universal constants if h s one of these

The theory of Bohr accounts well for the normal helium spectrum and less perfectly for the lithium spectrum (atom with nuclear charge $+3$)

The Rutherford hydrogen atom with the $-$ electron in orbital motion together with quantum assumptions seems thus to account for every thing except the observed magnetic quality we do not know however in what manner atomic H would behave magnetically

As I have shown it may be necessary to postulate special structure (magneton) or a rotating neutral doublet or a rotating nucleus in order to account for diamagnetic associated hydrogen

In addition to these investigations in the atom Bohr has examined the equilibrium of two such atoms when they approach one another closely and indicates how stability would be attained under purely electrostatic forces in a molecule in which the negative electrons are at opposite ends of a diameter in a common orbit

He is thus able to account for the necessary association of two atoms to form a molecule

It has already been shown in lecture IV that rotation of the nucleus itself would according to Honda and Okubo endow a molecule of this kind with diamagnetic quality

Langmuir has suggested that many difficulties which are experienced when the more complex atoms are examined may be met

by replacing the ordinary negative electron by the Ring Electron which has already been described Stationary electrons are then possible

Although Parson s atomic theory has been concerned chiefly with valency phenomena and has met with considerable success in regard to the periodic law of the elements yet if there is any truth in the conceptions involved the theory ought to be capable of explaining the properties of the hydrogen atom and molecule In the case of this simple atom the ring electron which it will be recalled can be of any diameter is regarded as surrounding the positive nucleus There i evidence that no radiation loss occurs in these circumstances It was shown that in the ring electron

the total angular momentum $= \frac{1}{2\pi} N \quad N$

where N is the number of magnetic tubes
and N electrostatic tubes

If now we identify the natural unit of action or angular momentum $\frac{h}{2\pi}$ with this electron we get

$$h = N \quad N$$

If further $N = e$ the natural unit of charge then

$$\frac{h}{e} = N$$

which is consequently $4\ 12 \times 10^7$ E M U There is therefore the possibility of reconciling this atom with Bohr s theory and Planck s radiation formula

Sir Joseph Thomson by assuming a change in the law of force within the atom has shown how stability of a rotating electron can be attained on the principles of classical dynamics alone It is to be borne in mind that Rutherford s experiments do not completely exclude the possibility of a change in the law of force at small distances though other interpretations of his results appear more plausible

It has already been remarked that there are two distinct ways of approaching the problem of atom structure one by observing and classifying the automatic records (spectra etc) and the other by direct experiment (and β ray scattering)

Similar to the method of spectra observation is that of chemical observation and chemists of recent years have urged that it is absurd for the physicist to build up an atom however ingenious and successful in other directions which fails to explain at least the *essentials* of chemical phenomena of which there is an enormous mass of classified data On these lines a striking departure from the orbital atom has been developed by Lewis and later by

is frequently 8 and never more than 8. The valency is called the polar number.

An atom, on this theory, is built up of—

(1) a kernel possessing an excess of + charge equal to the ordinal number in the Periodic Table group;
(2) an outer atom or shell, the number of electrons in which is equal to the excess positive charge on the kernel *when the atom is neutral*, but may vary during chemical change between 0 and 8;
(3) the atom tends to hold an even number of electrons in its shell, especially 8, which are arranged on the corners of a cube;
(4) two atomic shells can interpenetrate;
(5) electrons can easily pass from one place to another in the shell. But they are held by constraints which depend on the nature of the atom;
(6) electric forces for very near electrons do not obey the inverse square law.

Both on this theory and on that of Parson, using the ring electron, the conclusion is that the most stable form for the atomic shell is one in which 8 electrons are held at the corners of a cube.

When atoms combine they usually hold certain electrons in common (2 electrons for each chemical bond).

Langmuir has modified and extended Lewis' theory.

The primary postulates of the theory are these:—

Postulate 1.—The electrons are arranged about the nucleus in pairs symmetrical with respect to the equatorial plane. They are symmetrical with respect to a polar axis, and have secondary planes of symmetry passing through the polar axis and making angles of 45° with each other. The total number of electrons equals the atomic number of the element.

Postulate 2.—The electrons occur in shells whose mean radii are as 1, 2, 3, 4, and whose surfaces are consequently as 1, 2², 3², 4².

Postulate 3.—Each spherical shell is divided into cellular spaces. The cells occupy equal areas in the shells; all cells in any atom have therefore equal volumes.

The 1st shell contains 2 cells (by dividing the shell by the equatorial plane).

The 2nd shell (4 × the surface) contains 8 cells.

The 3rd shell (9 × the surface) contains 18 cells, and so on.

Postulate 4.—In general each cell can contain 2 electrons, but the innermost shell contains 2 only.

We cannot add electrons to the outer shell until all inner shells contain their maximum number of electrons.

There are several additional postulates the more important of which I quote from Langmuir's memoir

Postulate 5.—It is assumed that electrons contained in the same cell are nearly without effect on each other. But the electrons in the outside layer tend to line themselves up (in a radial direction) with those of the underlying shell because of a magnetic field probably always to be associated with electrons bound in atoms (Parson's magneton theory). This attraction may be more or less counteracted by the electrostatic repulsion between the outside electrons and those in the underlying shell. The electrons in the outside layer also repel each other and thus tend to distribute themselves among the available cells so as to be as far apart as possible. The actual positions of equilibrium depend on a balance between these three sets of force together with the attractive force exerted by the nucleus.

Postulate 6.—When the number of electrons in the outside layer is small the magnetic attraction exerted by the electrons of the inner shells tend to predominate over the electrostatic repulsion but when the atomic number and the number of electrons in the outside layer increase the electrostatic forces gradually become the controlling factor. As a result when there are few electrons in the outer layer these arrange themselves in the cells over those of the underlying shell but when the outside layer begins to approach its quota of electrons the cells over the underlying electrons tend to remain empty.

Postulate 7.—The properties of the atoms are determined by the number and arrangement of electrons in the outside layer and the ease with which they are able to revert to more stable forms by giving up or taking up electrons or by sharing their outside electrons with atoms with which they combine. The tendencies to revert to the forms represented by the atoms of the inert gases are the strongest but there are a few other forms of high symmetry such as those corresponding to certain possible forms of nickel palladium erbium and platinum atoms toward which atoms have a weaker tendency to revert (by giving up electrons only).

It is assumed that in a cell the two electrons are at different distances from the nucleus. Each shell therefore consists of two *layers* which may be called

I II II III III and so on

Helium contains 1 layer
Neon 2 layers
Argon 3 layers

Krypton contains 4 layers
Xenon 5 layers
Niton 6 layers

Thus the following table can be formed —

Shell	Radius	No of cells in hemisphere	No of cells	
			in axis	zone
I	1	1	1	0
II		4	0	4
III	3	9	1	8
IV	4	16	0	16

Therefore the number of cells arranged in zones is always a multiple of 4 and we get tetragonal symmetry for the inert gases

The idea of the cell which is regarded as having an independent existence independent of the electrons in it is related to Bohr s assumption of stationary states The passage of an electron from one cell to another is conceived to give rise to a spectral line

It is therefore only by a rearrangement of electrons caused by an interaction between atoms that Postulate 4 can be fulfilled

This is the basis of chemical action

Let us now consider how the application of the Postulate enables us to picture the external structure of the atoms of the inert gases and to what extent agreement with the Periodic System is attained

Hydrogen has atomic number $N = 1$ and the atom possesse one electron By Postulates 1 and 7 it is unsaturated and tends t take up an ele tron and become symmetrical Helium Hydrogen valency is therefore unity

In Helium ($N=2$) the first shel is complete with its 2 lec trons

In Lithium ($N = 3$) the extra electron must go alone into the 1st layer of the second shell II The electron is easily de tached and the atom is thus a univalent cation

If all the cells of shell II were filled by electrons we should have the Helium structure plus 8 electrons in shell II at the corners of a cube i e an element with atomic number 10 which is the next stable inert atom Neon There will be some shortenin along the polar axis owing to the two electrons in shell I Argon the next higher inert gas has an additional 8 electrons which com plete layer II_b The maximum valency of an element is thus determined by the number of electrons which would be given up

if the atom were to revert to the structure corresponding to the next lower inert gas

For instance up to $N = 17$ the maximum positive valency increases regularly up to the halogens (with the exception of Oxygen and Fluorine) In the case of carbon there are 4 electrons in shell II and these can arrange themselves at the corners of a tetrahedron With nitrogen no symmetrical arrangement of the 5 electrons in layer II is possible This as is shown by Langmuir leads nitrogen to form a series of very unusual compounds There is marked contrast between the constant valency of carbon and the variable valency of nitrogen the high melting point of carbon and the low melting point of nitrogen the stability of carbon compounds and the explosive properties of many nitrogen compounds Passing to the first Long Period beyond Argon (which is stable and inert and has all its cells filled with electrons 16 in addition to the 2 which form the Helium basis) we came first to Potassium ($N = 19$) and then to Calcium ($N = 20$) Here the third shell is just beginning and the properties of these two elements are similar to the properties of sodium magnesium and aluminium which immediately follow the inert and saturated neon

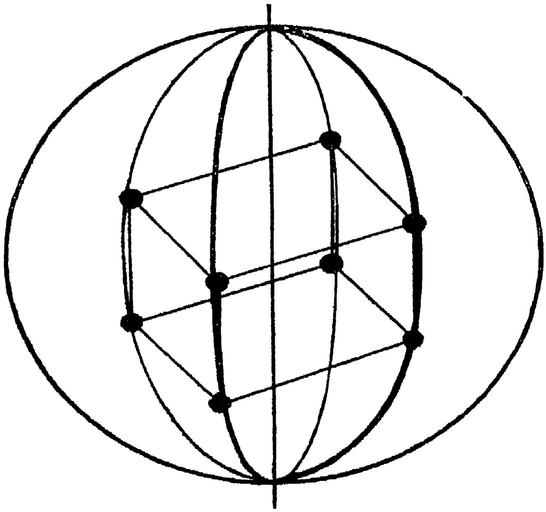


Fig 1

On these lines a most remarkable number of the chemical properties of matter are satisfactorily accounted for as also in detail the variation in property as we pass up the Periodic Table

ATOMIC NUMBERS AND ATOMIC WEIGHTS O H ELEMENTS

Atomic Number	Element	Atomic Weight	Atomic Number	Element	Atomic Weight
1	Hyd oge	1 008	4	S lve	10 88
2	Hel um	3 99	48	Cadm	11 40
3	L th um	6 94	4	Ind	114 8
4	Beryl u	9 1	50	T n	118
5	Boron	11 0	1	Ant mo	120
6	Ca bo	12 0	2	Tellu n	1 7
7	N trogen	14 01	53	Iod ne	1
8	Oxyge	16 00	54	Xeno	130
9	Fluor ne	19 0	5	Cae u n	132 81
10	Neon	20 2	56	Ba n	137 3
11	Sod um	23 00	5	La th	13 0
12	Mag es u	24 32	58	Cer u n	140 2
13	Alum n u	27 1	5	Praesody n um	140
14	S l co	28 3	60	Ne dym un	144 3
15	Phosphoru	31 04	61	——	——
16	Sulphu	32 06	62	Sa na un	1 0 4
1	Chlor ne	35 46	63	Lu op u	152 0
18	Argon	39 88	64	Godol u	157 3
19	Potass u	39 10	65	Te b n	159 2
20	Calc um	40 07	66	Dysp os	162
21	Scand u n	44 1	6	Holm um	163
22	T tan um	48 1	68	Erb u	16
23	Vanad m	51 0	6	Th l um	168
24	Ch om u n	52 0	0	Ytte b u	1 3
25	Manga ese	54 93	71	L tec n	17 0
26	Iron	55 84	72	——	——
27	Cobalt	58 97	73	Ta talum	181
28	N ckel	58 68	4	Tu g te	184 0
29	Copper	63 57	75	——	——
30	Z nc	65 3	6	Osmium	190
31	Gall un	69 9		Ir d um	193 1
32	Ge man un	2 5	78	Plat n n	1 2
33	Ar en c	74 96	79	Gold	1 7
34	Selen n	9 2	80	Mercu y	00
35	Bro n ne	79 92	81	Tl all	04 0
36	Krypton	82 92	82	Lead	20
37	Rub d u n	85 45	83	B s nuth	208 0
38	Stront m	8 63	84	Polo m	10 0
39	Yttr um	88	85	——	——
40	Z rcon um	90 16	86	Ema ato	0
41	N ob um	93 5	87	——	——
42	Molybdenu n	96 0	88	Ra n	2 0
43	——	——	89	Act um	227 0
44	Rl uthen um	101	90	Thor um	232 1
45	Rhod um	102 9	91	Uran um X	234 0
46	Palad um	106	92	Ura um	38

LECTURE VI

Having considered in some detail the kind of structure which we are led to assign to the atom as a result of observation on spectra, magnetism and particle scattering, together with general theoretical reasoning based on the phenomena of radiation, we are in a position to review some important recent work on the relations between different kinds of atoms as they occur in the universe. Two lines of experimental research stand out predominately in this connection: the first established a most remarkable relation between the numbers of electrons contained in the atoms of elements of ascending atomic weight, the second was concerned with a new and exceedingly accurate method of comparing atomic weights and led to the discovery that in all instances at present examined the atomic weight of a real element is an integral number to within one part in one thousand and that fractional atomic weights as usally determined by the chemist are merely evidence of the existence of a *mixture* of two or more real elements.

Let us first consider the experimental work which led Moseley[1] to his generalization concerning the number of negative electrons in element atoms.

The results emerged from an elaborate research on the characteristic X radiation emitted by elements when exposed to Rontgen Rays. It has been established for many years (since 1908 in fact) that when X rays (of approximate wave length 10 cms.) fall on a substance the following secondary phenomena usually occur:—

(i) Scattered *X* radiation of all wave lengths is given off from the material.

(ii) X rays of special frequencies (like the special frequencies of spectral lines) are emitted characteristic of the material on which the primary X rays fall.

(iii) Some negative electrons are ejected.

The principal phenomena connected with characteristic radiation are well known; it is recognized that

(*a*) the characteristic radiation is always less penetrating than the primary radiation which excited it.

(*b*) The higher the atomic weight of the material giving the characteristic ray the harder or more penetrating are these rays.

(*c*) Sometimes two kinds of characteristic radiation are emitted by the same element—in any case two distinct types are

---

[1] The suggestion that the atomic number represented the number of external negative electrons in the atom was first made by Van den Broek.
The reader [illegible]

cognized by widely differing wave lengths are well known some elements emit one type some the other some as I have said both types The two kinds are known as the K radiation which is the more penetrating and the L radiation which is softer The group of wave length constituting the L radiation is some eight times larger than that forming the K type

If we measure the absorption coefficient λ in aluminium (say) of the characteristic radiations from different elements and form $\frac{\lambda}{\rho}$ where ρ is the density of aluminium we get the mass absorption coefficient for that particular radiation

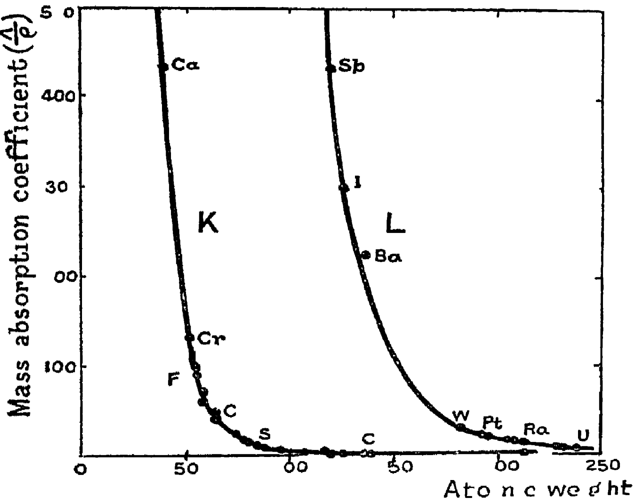


Fig 16

It is found on plotting $\frac{\lambda}{\rho}$ for the characteristic rays from different elements against the atomic weight of the element that the two groups K and L lie on two quite definite curves which show clearly the distinct nature of the different type of radiation (Fig 16) It is highly probable that the K and L radiations are emitted by quite distinct group of electrons in the atom the K type from a deep seated group near the nucleus the other by an outlying group nearer the surface of the atom

Now elements are transparent to their own characteristic radiations but if the wave length of X rays impinging on a plate of any element is rather smaller than either K or L radiation a

marked *absorption* occurs immediately below the transparency wave length This is most easily seen from fig 17

These facts lead up to the special discoveries of Moseley which were made possible by the well known phenomenon discovered by Laue and developed by W H and W L Bragg that X rays are diffracted by a crystal the crystal atoms acting as a space diffraction grating

Moseley used a potassium ferrocyanide crystal and obtained the diffraction spectra of a large number of elements Confining our attention to the more penetrating type the spectra in most cases consisted of two lines only one of which was intense and was what had hitherto been recognized as the *K* radiation The other

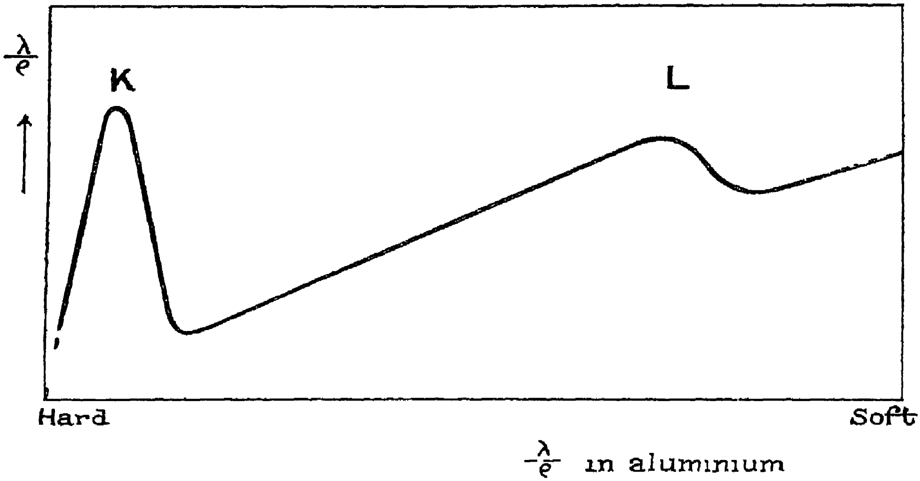
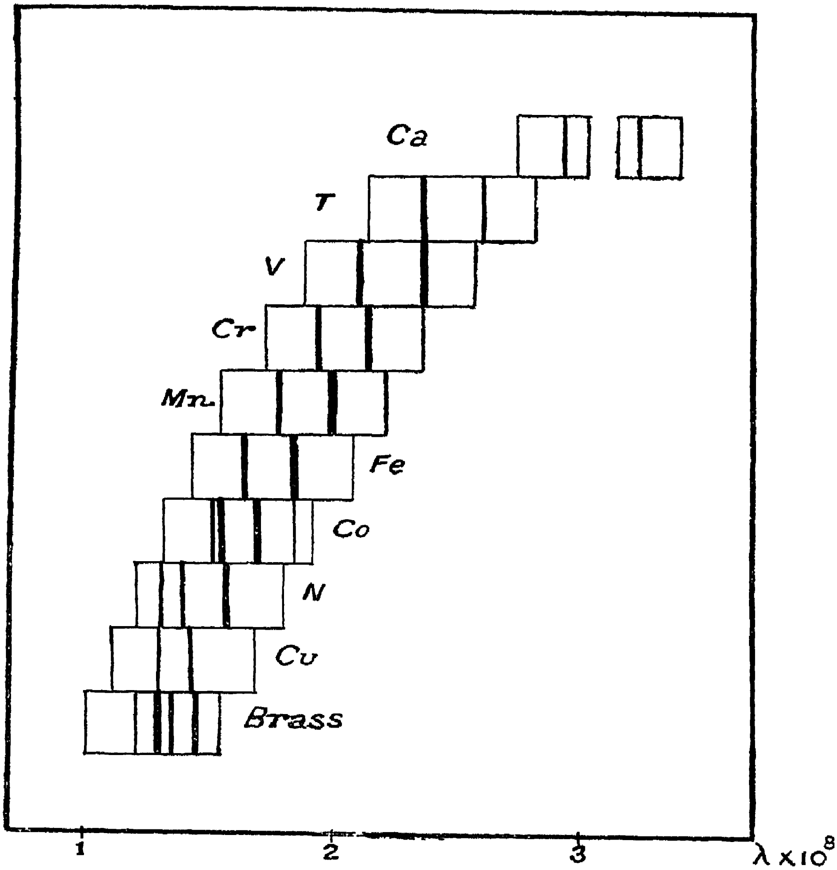


FIG 17

line represented of course a neighbouring and less intense group of waves of slightly smaller wave length which the crystal disentangled Possessing the photographs of these X ray lines which it will be seen from Fig 18 increase in wave length from element to element in an exceedingly regular manner it is easy to find the frequency of the X ray vibration corresponding to each line and hence to plot $\sqrt{\nu}$ against the atomic weight of the element No very conspicuous peculiarity is to be seen on doing this save that the two variables $\sqrt{\nu}$ and the atomic weights increase generally together If however the elements are arranged in *ascending order* of atomic weight and if they are labelled 1 2 3 etc according to their serial number in the list and if further these

atomic numbers are plotted against $\sqrt{\nu}$ the result is most remarkable.

To within the limits of accuracy with which ν is known the



Thick lines are K radiation

Fig 18

curve is seen to be a straight line indicating that $\sqrt{\nu}$ is a linear function of the atomic number of the element, $\sqrt{\nu}$ in other words forms an arithmetical progression as the atomic number increases.

It is suggested by Moseley and now generally accepted as true that for two elements

$$\frac{\sqrt{}}{\sqrt{}}=\frac{\text{nuclear charge on element atom 1}}{\text{nuclear charge on element atom 2}}$$

and that the atomic number actually represents the net nuclear charge of the atom The physics of the phenomenon is doubtless this that the vibrations observed are from a deeply seated group of electrons near the nucleus that they are therefore in the very intense field of force due to the nuclear charge and that their vibration frequencies naturally form a measure of the magnitude of that charge

It is accepted then that the atomic or Moseley number is the net charge on the nucleus in terms of hydrogen and is therefore equal to the number of external non nuclear electrons in the atom

Moseley s result can be represented by the formula

$$\sqrt{\nu}=AN-b$$

where N is the atomic number of the element and A and B are constants depending on the type of X ray line employed

We also deduce according to the results described above that the net nuclear positive charge = the number of external electrons in atom $=Ne$

Let us now pass to the second series of researches to which I referred those connected with the atomic masses of the elements The line of investigation pursued begins with the discovery by Goldstein in 1886 of positively charged masses in a vacuum tube which proceed from a perforated cathode in the opposite direction to the cathode rays The theory of the motion of these particles in a magnetic field is as follows —

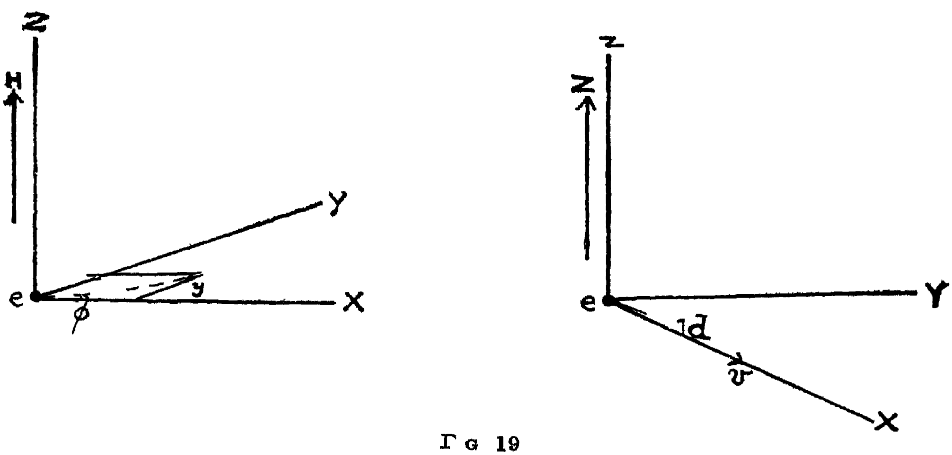


FIG 19

Let the particle charge e mass m be moving along the X axis and let the magnetic field H be parallel to the Z axis Fig 19 a

Then the force on the charged particle is along the Y axis and the equation of motion is

$$m\frac{d^2 y}{dt^2} = eH\frac{dx}{dt}$$

therefore

$$m\frac{dy}{dt} = \int eH\frac{dx}{dt}\,dt + C$$

There will be a small deflection d in the XY plane Now v the actual velocity in the path is approximately

$$\frac{dx}{dt} \quad \text{if } d \text{ is negligible}$$

and

$$\frac{dy}{dt} = \frac{dy}{dx}\,\frac{dx}{dt} = \frac{dy}{dx}\,v$$

also when

$$x = 0 \qquad \frac{dy}{dt} = 0 \qquad C = 0$$

Hence

$$mv\frac{dy}{dx} = \int eH\,dx$$

when $x = l$ let the deflection be y

then

$$mvy = \int\left\{\int eH\,dx\right\}dx$$

Put

$$\int He\,dx = w \quad \text{and} \quad x = u$$

then

$$\int\left\{\int He\,du\right\}dx = \int w\,du = \Big[wu\Big]^l - \int u\,dw$$

$$= \left[x\int He\,dx\right]^l - \int xHe\,dx$$

and

$$mvy = l\int He\,dx - \int^l xHe\,dx$$

$$= e\int (l-x)\,H\,dx = eA$$

where A depends only on the field and the distance from the point of projection at which y is measured

$$y = \frac{e}{mv} A$$

In an electrostatic field Z (Fig 19 b)

$$m \frac{d^2 z}{dt^2} = eZ$$

or

$$mv^2 \frac{d^2 z}{dx^2} = eZ$$

giving

$$z = \frac{e}{mv^2} B$$

where

$$B = \int^{l} \left(\int Z \, dx \right) dx$$

and is independent of charge mass or velocity If the fields are simultaneously applied and are perpendicular to one another

$$y = \frac{e}{mv} A \qquad z = \frac{e}{mv^2} B \qquad (1)$$

and

$$\frac{e}{m} = \frac{y^2}{z} \cdot \frac{B}{A^2} \qquad (2)$$

$$v = \frac{y}{z} \cdot \frac{B}{A} \qquad (3)$$

If therefore a stream of particles of different values for $\frac{e}{m}$ are projected with different velocities along the X axis and fall on a screen they get sorted out All particles striking the same point on the screen must have the same speed and the same $\frac{e}{m}$ Thus if we know the deflected position for a particle or group of particles we can get v and $\frac{e}{m}$ from equations (2) and (3)

It is clear that for particles of fixed v $\frac{z}{y}$ is constant and all such particles lie on a straight line through O the undeflected position Fig 20 For particles of fixed $\frac{e}{m}$ (same *kind* of particle) $\frac{y^2}{z}$ is constant Thus all such particles lie on a parabola with vertex at O There will be one such parabola for each kind of particle and the velocity of the particle which strikes at P is proportional to tan ϕ

Thus masses could be compared by measuring the ordinates of two parabolas for the same value of y provided the particles had the same charge.

For instance in fig.

$$\frac{Sa}{Sb} = \frac{\frac{e}{m_1}}{\frac{e}{m}} = \frac{m}{m_1}$$

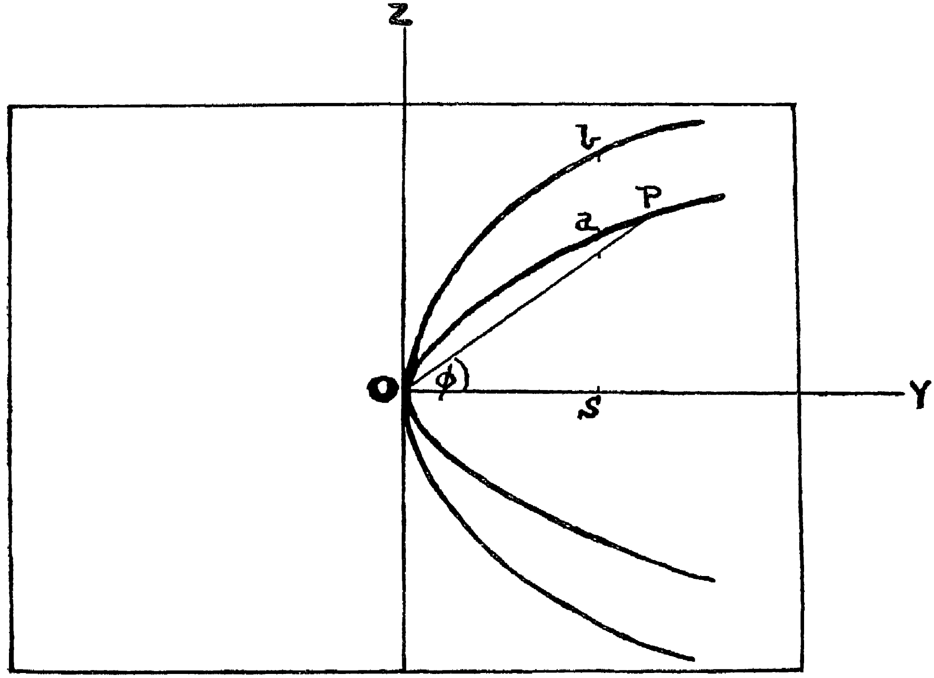


Fig. [illegible]

This was the method employed by Sir J. J. Thomson who obtained an enormous amount of information concerning the types of positively charged atoms of matter in tubes containing different gases.

Aston took up the problem of trying to get a much higher precision in the measurements. The chief practical difficulty is to obtain a sufficiently thin parabola for accurate measurement of the ordinates. When by stopping down the beam of rays the parabola is made very fine the loss of intensity is so great that the parabola ceases to be visible on the plate. Aston developed a

method for focussing the spot so as to give a real positive ray spectrum where deflections are proportional to $\frac{m}{e}$ and independent of v over a certain range The secret of his experimental success in this very important work was the employment of parallel instead of crossed fields The principal of Aston s method is shown in figure 6

The rays after passing two special slits S and S Fig 21 traverse (as a narrow ribbon) the electrostatic field and are spread out thereby into an electric spectrum A limited width of th latter is selected by the diaphragm D and passes the magnetic field (produced by pole pieces of circular cross section) which deflects the portions of the narrow electric spectrum in the *opposit*

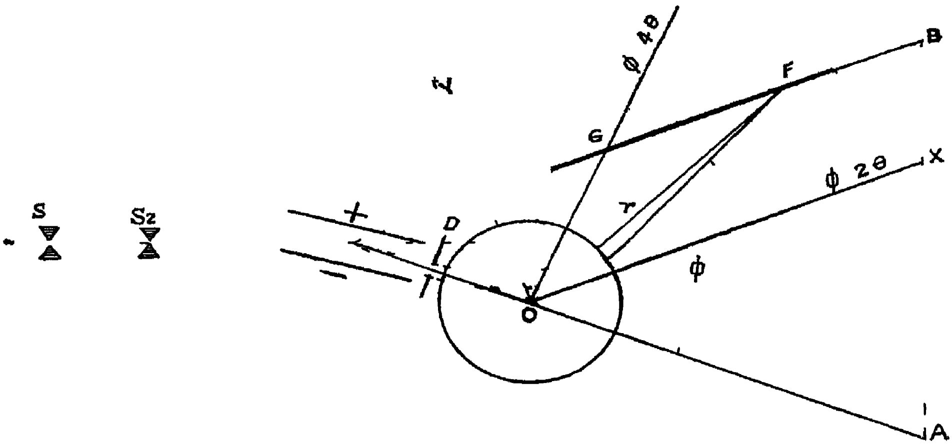


FIG 1

direction The spectrum finally falls on a photographic plate at FG which is placed at the focus or position of minimum width of band Naturally the whole arrangement as indicated is enclosed in an exhausted vessel at the back of the perforated cathode

Take the electric and magnetic fields Z and H parallel and remember that now equations (1) become

$$\delta = \frac{\ }{mv} A \text{ and } \delta = \frac{e}{mv} b$$

where δ and δ are the linear deflections produced by the magnetic and electrostatic fields respectively

Then from the geometry of the figure it is easily shown that

$$A = \frac{L}{2} H \text{ and } B = \frac{l^2}{2} Z$$

where L is the length of the path of the rays in the magnetic field and l is the length of path in the electric field

Hence for small angles if θ is the angle through which the beam is bent by the field Z and ϕ the angle through which it is bent by the field H we have $\delta = l/\ \theta$ and $\delta = L/\ \phi$

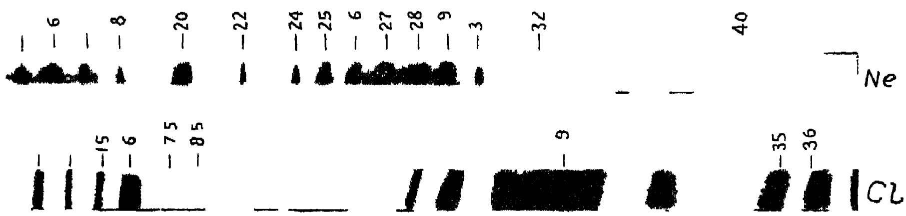
so that
$$\frac{e}{m} = \frac{\theta}{lZ}$$

and
$$\frac{e}{mv} = \frac{\phi}{LH}$$

Thus θv^2 and ϕv are constant (for the small range let through by the diaphragm) for all rays of fixed $\frac{e}{m}$

$$\theta v^2 = \text{const} \qquad \phi v = \text{const}$$

So that we have
$$\frac{d\theta}{\theta} = 2\frac{dv}{v} \quad \text{and} \quad \frac{d\phi}{\phi} + \frac{dv}{v} = 0$$



Fig

therefore
$$\frac{d\phi}{d\theta} = \frac{\phi}{2\theta}$$

when the velocity varies in a group of given $\frac{e}{m}$. The problem is now to find the breadth of the strip or ribbon of particles and to see when this vanishes. This position gives the focus and the plate is placed at the focus for instance at F

The breadth at O is $bd\theta$ where b is the distance from O to the centre of the electrostatic field. At a distance r from O the breadth

$$= b\,d\theta + r(d\theta + d\phi)$$
$$= d\theta\left[b + r\left(1 + \frac{\phi}{2\theta}\right)\right]$$

This is shown to vanish when

$$r(\phi - 2\theta) = 2b\theta$$

or referred to axes OX, OY the focus coordinates are $r\cos\chi$ and $r\sin\chi$ where

$$\chi = (\phi - 2\theta)$$

so the foci lie on a straight line GH parallel to OX. The field can be adjusted to use the brightest part of the electric spectrum and values of $\frac{e}{m}$ are represented by the various lines and can be compared by referring their positions to those of standard elements.

Since the method is a comparison of masses it is clearly necessary to have a standard known mass or masses to start with. An example of Aston's results is shown in Fig. 22.

It must be remembered that the lines may be due to the atom singly or multiply charged (1st and 2nd order spectra) or to the molecule (nearly always 1st order). Oxygen and Carbon give extremely exact integral relations between their atomic weights and this is evidence that they are pure elements. Other standards are C (6) C(12) CO(28) CO (64). As an example of one of the first discoveries made by this method we may consider the case of neon whose ordinary atomic weight is 20 2. The mass spectrogram shows that neon consists of two *isotopes* of masses 20 and 22 with a slight possibility of a third of mass 21.

Chlorine (35 46) shows no *indication* of a line at 35 46 but gives a group at 35 36 37 38 and two secondaries 17 5 and 18 5.

Cl^{35} and Cl^{37} are regarded as the isotopes lines at 36 and 38 being due to HCl^{36} and HCl^{37}.

Nitrogen (14 01) gives the same line as CH while its molecule gives the same line as CO.

Hydrogen (1 008) is a pure element.

Xenon has lines 128 130 131 133 135 while krypton shows lines at 80 82 83 84 86 and a faint line 78 together with multiply charged clusters of the same relative intensity.

The 2nd order krypton can be compared with argon (40) with very great accuracy.

The general conclusion which is to be drawn from these experiments is that all masses atomic or molecular element or compound are whole numbers to within 1 part in 1000. Fractions in atomic weights are merely statistical effects due to the relative quantities of the isotopic constituents. (*Aston*)

If a positive electron and a negative electron both enter another nucleus an isotope results if only the positive electron enters an element of next higher atomic number results (the charge increases).

The hydrogen atom *on this scale* gives a mass 1 008 i.e. greater than unity. This is probably because electromagnetic masses are only additive when at a distance, when closely packed

Now the odd elements are much less abundant in nature than the even elements a fact which suggests that odd elements are less stable owing to the presence of the group just mentioned This entity $(\eta\beta)$ is clearly an isotope of hydrogen It has the same net charge as the hydrogen nucleus and a different mass If it exists separately its atomic weight is 3

As has appeared from other evidence the helium nucleus presumably has the structure

$$\eta\beta$$

i e two positive charges and atomic weight 4

Harkins suggests that $\eta\beta$ is arranged with the three protons in a chain and the two negative electrons rotating in planes parallel to the chain and in opposite sides of it The group $\eta_1\beta$ would consist of an assemblage of 4 protons at the corners of a square the two negative electrons lying on either side of the central group

It is admitted that the elements of low atomic weight fall into line with the scheme just described far better than those of high In fact above atomic number 28 the rules do not hold satisfactorily Harkins suggests as the reason for this failure that elements above 28 are practically all mixtures of isotopes The suggestion is borne out by Aston s more recent work

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